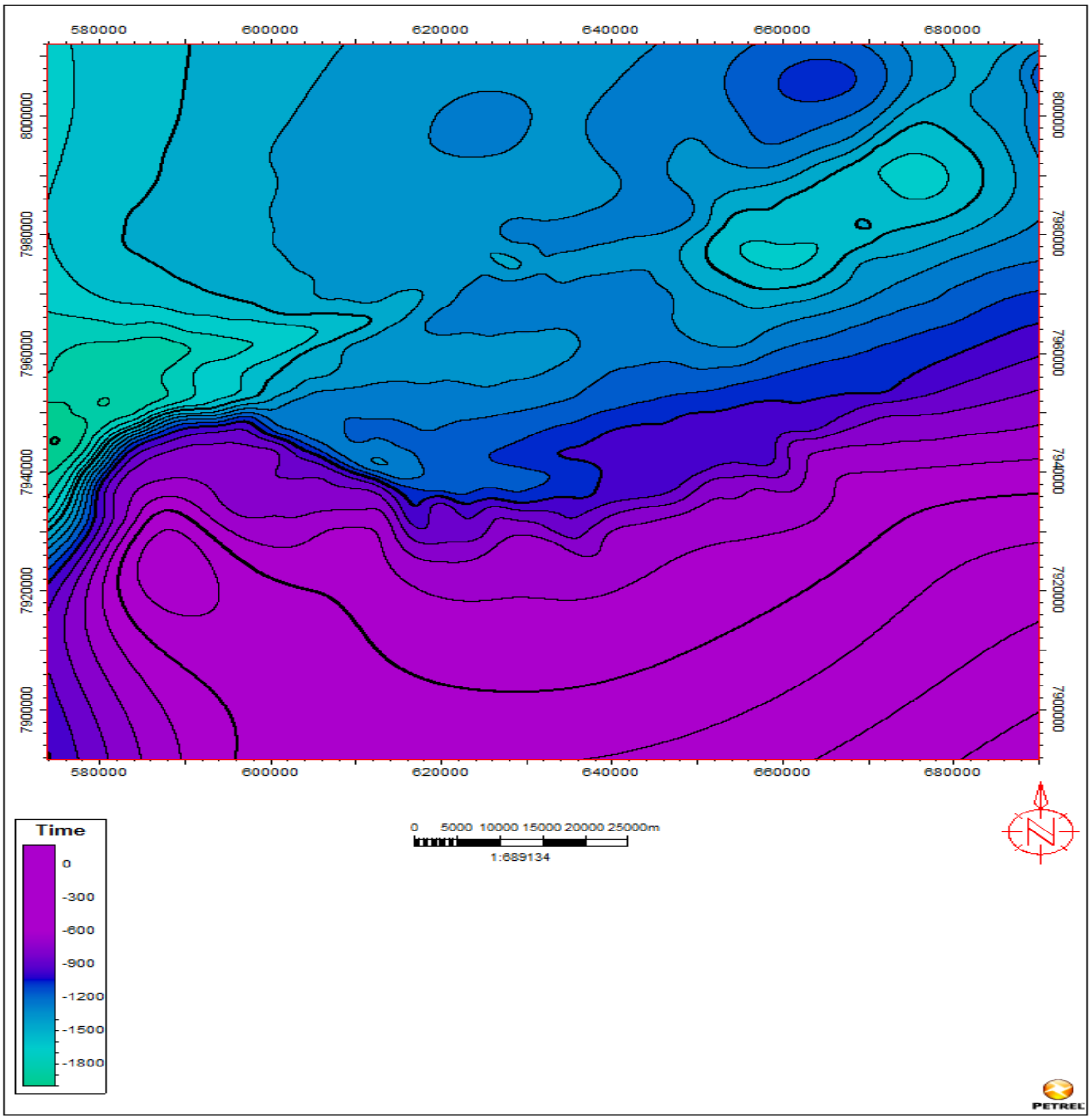
Master Thesis in Geosciences

Structural analysis of the Måsøy Fault Complex in the SW Barents Sea

Muhammad Aftab



UNIVERSITY OF OSLO

FACULTY OF MATHEMATICS AND NATURAL SCIENCES

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Discipline: Petroleum Geology and Geophysics

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Abstract

Study area for this thesis work is the Måsøy Fault Complex located in the SW Barents Sea, which is the southern basin marginal fault of the Nordkapp Basin. It represents the structural separation between the Nordkapp Basin and the Finnmark Platform. For the detailed structural analysis of the study area 2D and 3D seismic data have been used along with three different wells in order to have a proper Stratigraphic control. All interpretation work has been carried out using Petrel (edition 2009).

The Måsøy Fault Complex is basically an extensional structure and is characterized by one major high-angle normal fault indicated by three contrasting strikes from west to east. On the basis of different strikes the fault complex can be divided into three segments. In segment 1 the strike is SW-NE, in segment 2 the strike is NW-SE and segment 3 has a SW-NE strike. The hanging wall of the major fault is more deformed as compared to the footwall. The entire area is dominated by normal faults along with minor influence of inversion. Partial impact of halokenesis has also been observed. The dominant striking trend of the minor faults is NE-SW.

On the basis of results and previous studies it has been noticed that Måsøy Fault Complex is associated with thick skin tectonics. The study area underwent two different rift phases. The first rift phase initiated during Late Devonian to Early Carboniferous and the second rifting event took place during Mid Jurassic to Early Cretaceous. During the tectonic evolution of the Måsøy Fault Complex it has been observed that major fault was active during different times resulting in fault controlled subsidence.

Key words: Måsøy Fault Complex, SW Barents Sea, Nordkapp Basin, Finnmark Platform, major normal fault, thick skin tectonics, halokinesis, inversion.

Contents

1. INTRODUCTION

Barents Sea is an epicontinental sea located on the NW margin of the Eurasian continental shelf. It is surrounded to the north and west by passive margins that are relatively younger in age. These margins were formed due to the opening of the Norwegian-Greenland Sea and the Eurasian Basin during Cenozoic time. The northern part of mainland Norway delineates the Barents Sea to the south and Novaya Zemlya to the east (Faleide et al. 1993) (Figure 1.1).

In terms of geology the Barents Sea is a complicated merge of basins and platforms. The sedimentation in the area started in Devonian times. The formation of Barents Sea is associated with two major continental collision events. First event was the Caledonian orogeny that ended about 400 million years ago. The result of this collision was the arrangement of the Baltic Plate and Laurentian plate with the Laurasian continent. Second event was the collision of Laurasian continent and Western Siberia that ended about 240 million years ago and resulted in the formation of eastern margin of Barents Sea (Dore 1994).

There are some deep sedimentary basins present in the southwestern Barents Sea. Formation of these basins is related to the regional tectonic events that took place within North Atlantic and Arctic areas (Faleide et al. 1993). Western part of the Barents Sea show more pronounced tectonic activity throughout Mesozoic and Cenozoic times. On the other hand eastern and northeastern areas since Late Carboniferous are marked by rather stable platforms and show less tectonism. Tectonic history of the area prior to Carboniferous is not well known however it is assumed that major structural development started in Devonian times and also some of the tectonic events could be associated with Caledonian Orogeny (Gabrielsen et al. 1990).

In terms of petroleum potential the Barents Sea is considered to be important. The petroleum activities in Barents Sea started in early 1980's. And since then large amount of data has been acquired and also drilling has been carried out at many places (Gabrielsen et al. 1990). Sea and land regions in the European Arctic area are occupied by Russia and Norway. Considering the both countries more than 100 wells have been drilled in the Barents Sea gion (Austvik 2007). Ample well information gave a proper control in order to extend the seismic survey on larger scale (Larsen et al. 2002).

Due to the present pace of consumption, oil reserves of the world are likely to reduce by the mid of 21st century (Campbell 1991, Lerche 1992) this can result in increase of demand and decrease in supply. Hence there is a great possibility that attention will be more towards the areas like Barents Sea in order to meet the energy demands of the world (Dore 1994).

The study area for this thesis work is Måsøy Fault Complex that separates the Finnmark Platform and the Nordkapp Basin. During the thesis work main emphasis will be upon the tectonic evolution of the study area. Which include the study of following parameters structural style, tectonic uplifting, timing of fault activity etc. And ultimately this will be helpful in understanding the regional tectonics.

Figure 1.1: Location of the Barents Sea (Google images).

2. Regional tectonic setting

North Greenland, Svalbard and Barents Sea areas are associated with the formation of two different rift networks. These rift systems were developed during Late Paleozoic and the sediments were deposited in relatively stable platforms and subsiding basins (Stemmerik & Worsley 2005). These rift systems are associated with the tectonic activities that took place in North Atlantic and Arctic areas. Ultimately both of these regions were connected through a mega rift zone known as the De Geer Zone (Faleide et al. 1993).

Most important sedimentary basins in terms of extent and sedimentation are present on the western side of Novaya Zemlya. These basins are North Barents Sea, North Novaya Zemlya Basin and South Barents Sea. These basins acted as major sites of deposition of sediments which were sourced by Urals during Late Paleozoic to Mesozoic times (Gramberg 1988).

About 12 km thick Permian and younger rocks are present in these basins. The line of these basins ends in the SE Barents Sea where the thickness of Permian sediments is about 2 to 3 km. This area is characterized as a structural extension of onshore Timan-Pechora Basin and is described by a NW to SE tectonic style associated with Late Precambrian tectonic activity (Dore 1994).

The structural development of the Barents Sea is associated with numerous tectonic events. The major structural trends associated with continental shelf of the Barent Sea are, ENE-WSW to NE-SW and NNE-SSW along with the limited effect of WNW-ESE trend. To the south an area which has an ENE-WSW trend is marked by major fault zones bordering the Nordkapp and Hammerfest basins (Gabrielsen et al. 1990) (Figure 2.1).

2.1 Geological evolution

2.1.1 Devonian to Carboniferous

After the Caledonian Orogeny, Late Silurian to Early Devonian was a time of large scale erosion due to the exposure of sediments (Smelror et al. 2009). Late Devonian to Early Carboniferous is marked by a change in stress system, from compressional regime to extensional regime. In result rift basins were formed followed by the deposition of continental sediments (Faleide et al. 1984).

Late Devonian to Early Carboniferous extension associated with the initial rifting between Greenland and Norway is the oldest event that can be observed in the western Barents Sea. The formation of Nordkapp Basin, Maud, Fingerdjupet, Tromsø and Ottar basins is associated with this age, along with Hammerfest Basin which could be originated during the same time (Gudlaugsson et al. 1998).

2.1.2 Middle Carboniferous to Permian

Most of the Barents Sea was stable in terms of tectonic activity from Late Carboniferous to Permian times. Tectonic activity was restricted to the western part. In the western part the main structural trend was NNE to SSW and NE to SW (Gabrielsen et al. 1990). Carboniferous is characterized by N-S trending faults. The rotated fault blocks of Carboniferous age at Bjørnøya were covered by Early Pemian carbonates (Riis et al. 1986). During Late Permian there was a regional subsidence along with the development of sag basin in the Barents Sea. At the same time faulting associated with rifting was also active (Glørstad – Clark et al. 2010).

2.1.3 Triassic to Jurassic

Two main events were dominant during Middle to Late Jurassic, including extension on regional scale and slight strike-slip activity along the older faults (Faleide et al. 1993).
Different tectonic activities resulted in normal faulting, tilting, uplifting and erosion during Late Permian to Early Triassic. Up till Middle to Late Jurassic the tectonic activity was less. During the Middle and Late Triassic the Loppa High was leveled off and got buried (Riis et al. 1986).

2.1.4 Late Jurassic to Early Cretaceous

Exact dating of tectonic activity younger than the Triassic is a bit difficult in most areas of the Barents Sea due to erosion. However in southern and western areas most of the sediments are preserved. In the Middle to Late Jurassic tectonic activity started in the Troms area, this resulted in block faulting that were having SW to NE and E to W trends. There is a possibility that N to S trending subsidence of Bjørnøya and Tromsø basins was originated during the same time (Riis et al. 1986).

Along with the formation of Senja Ridge the deformation sustained in the Early Cretaceous. During the same time tectonic activity continued along the transition zone between eastern stable platform and the western Cretaceous basins. The major Cretaceous tectonic stage is indicated by the folding and faulting in the Senja Ridge. In the Late Cretaceous this activity was ended, followed by the uplift (Riis et al. 1986).

2.1.5 Tertiary Deformation

Wrench movements along the SW to NE trends sustained in the early Tertiary. This phase of wrenching during Tertiary can be associated with the opening of the Norwegian-Greenland Sea. Due to a changed spreading pattern in Oligocene there was a significant uplift (Talwani & Eldholm 1977, Myhre et al. 1982). There was a deposition of sedimentary wedge which was followed by erosion. The massive part of this wedge is present on the Senja Ridge and in the western portion of the Bjørnøya Basin (Riis et al. 1986).

In the entire Barents Sea during Neogene there was erosion associated with uplift followed by the deposition of thick sequences into the oceanic basins to the north and west. This was resulted due to the glaciations in northern hemisphere (Faleide et al. 1996).

2.2 South west Barents Sea

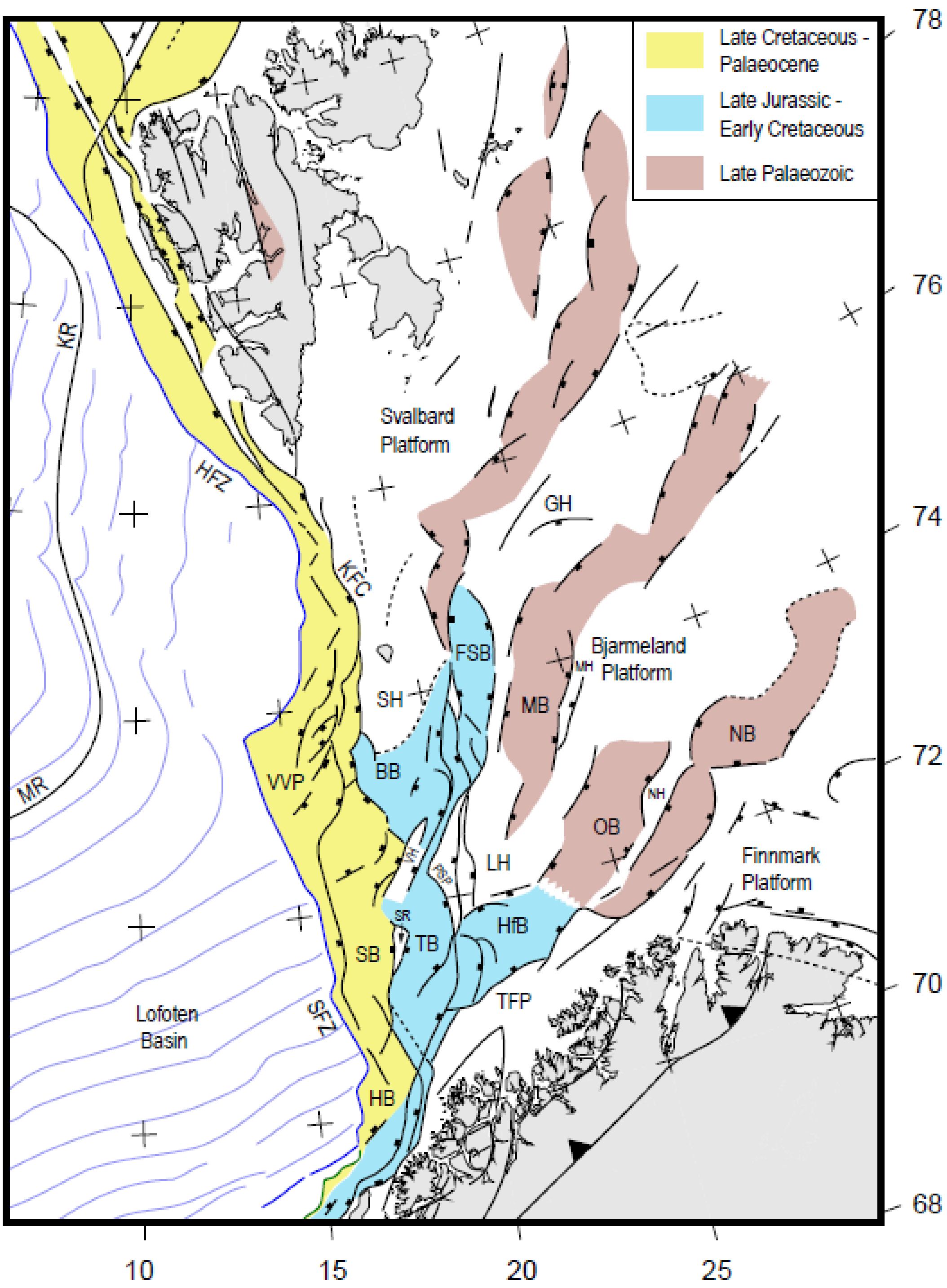


Figure 2.1: Major structural elements of the western Barents Sea and bordering areas (Faleide et al.2010). BB = Bjørnøya Basin FSB = Fingerdjupet Sub-basin, GH = Gardarbanken High, HB = Harstad Basin, HfB = Hammerfest Basin, HFZ = Hornsund Fault

Zone, KFC=Knølegga Fault Complex, KR = Knipovich Ridge, LH = Loppa High. MB = Maud Basin MH = Mercurius High, MR = Mohns Ridge, NB = Nordkapp Basin, NH = Nordsel High, OB = Ottar Basin, PSP = Polheim Sub-platform, SB = Sørvestsnaget Basin, SFZ = Senja Fracture Zone, SH = Stappen High, SR = Senja Ridge, TB = Tromsø Basin, TFP = Troms-Finnmark Platform, VH = Veslemøy High, VVP = Vestbakken Volcanic Province

2.2.1 Oceanic basin

The formation of Lofoten Basin is associated with the seafloor spreading in the Norwegian Greenland Sea during Cenozoic. The oceanic crust next to the continent-ocean boundary is indicated by high velocities values. Further seawards the character of the oceanic crust changes (Jackson et al. 1991, Faleide et al. 1993).

2.2.2 Continent ocean transition

The continent-ocean transition is narrow along the Senja Fracture Zone (Faleide et al. 1991). From a major continental marginal fault next to the Senja Fracture Zone, the oceanic basement in the Lofoten Basin can be tracked within a distance of about 10 km (Faleide et al. 1993) (Figure 2.1).

2.2.3 Tertiary marginal basin

The tectonic activity that occurred during the Tertiary break up affected the Sørvestsnaget Basin. Older structures present under the intrabasinal highs (Stappen High, Veslemøy High, Senja Ridge) control the basin configuration. To the west of Senja Ridge the uplifted crust indicates the Early Tertiary opening along the Senja Fracture Zone. In Early Eocene the main deformation resulted during the initial breakup. However some of the faults show Oligocene tectonic activity but it is not prominent (Faleide et al. 1993) (Figure 2.1).

From the uplifted outer margin about 1 km of Palaeogene sediments were eroded and further deposited into the ocean basin. There was regional subsidence along with uplift and erosion of the Barents Sea province in the east during Oligocene, which resulted in the development of large scale post-Oligocene sedimentary wedge (Faleide et al. 1993).

2.2.4 Cretaceous basins

There was a massive sedimentation and subsidence during Cretaceous in the Tromsø, Harstad and Bjørnøya basins. Regional studies (Rønnevik and Jacobsen. 1984, Faleide et al. 1984) along with the halokinesis in the Sørvestsnaget and Tromsø basins indicate that pre-Middle Jurassic succession may contain massive Triassic and Jurassic clastic sediments, along with Permo-Carboniferous evaporates and mixed carbonates (Faleide et al. 1993) (figure 2.1).

The sediments in the Harstad Basin are disturbed due to the numerous stages of extensional tectonics, which perhaps initiated in the Middle Jurassic and sustained during the phase of main subsidence in the Early Cretaceous. Particularly to the south of the basin there is a large scale listric faulting which is associated with the hanging wall rollover anticlines. Further in Late Cretaceous and Tertiary normal faulting started again (Faleide et al. 1993).

2.2.5 Intrabasinal highs

In the SW Barents Sea intrabasinal highs are not completely understood. During several tectonic events these highs were active and later on within the Cretaceous basin province these were affected by inversion events during Late Cretaceous and Early Tertiary tectonic stages and differential subsidence (Faleide et al. 1993) (Figure 2.1).

The Velsemøy High divides the Bjørnøya and Tromsø basins. It is associated with deep rooted westward oriented faults and these faults mark the southwards extension of the Bjørnøyrenna Fault Complex. The effects of tectonic inversion in Velsemøy High and Senja Ridge are associated with the strike-slip tectonic events along the Bjørnøyrenna Fault Complex (Faleide et al. 1993) (Figure 2.1).

Bjørnøya is delimited by Stappen High. From Late Palaeozoic to Jurassic times in the western Barents Sea Stappen High was a part of N-S trending uplifted area. The tectonic activity along the De Geer Zone directly affected the local Cretaceous subsidence and Tertiary uplift. The southern border of the Stappen High was formed due to the partial Tertiary inversion of the Bjørnøya Basin (Faleide et. al. 1993) (Figure 2.1).

2.2.6 Cretaceous boundary faults

The eastern boundary faults were originated during Early Cretaceous representing the extensional tectonics. The structural trend changes along the strike, and listric faults dominate the Bjørnøyrenna Fault Complex and the southern Troms-Finnmark Fault Complex. The major stage of subsidence initiated in the Middle Jurassic and ended in the Early Cretaceous. There is an indication of reactivation of tectonic activity in the Late Cretaceous along with minor compressional factor. This faulting has also affected Tertiary rocks (Gabrielsen et al. 1990, Faleide et al. 1993) (Figure 2.1).

The southern part that is bordering the Harstad Basin can be considered as a part of the Troms-Finnmark Fault Complex (Gabrielsen et al. 1990). However in terms of tectonic extension and basin formation in Mesozoic, this part must be regarded as southern extension of the Ringvassøy-Loppa Fault Complex (Faleide et al. 1993) (Figure 2.1).

The rotated fault blocks that characterize the Ringvassøy-Loppa Fault Complex are indicating a terrace which is cross cutting the Hammerfest Basin (Gabrielsen et al. 1984). Further north listric fault geometry characterizes the Bjørnøyrenna Fault Complex, and in Permian rocks this listric fault geometry seems to be flattening into a detachment (Faleide et al. 1993).

Bjørnøya Basin is separated by the Leirdjupet Fault Complex and it is divided into two different zones, shallow eastern zone and deep western zone. To the south this zone is marked by a major fault that is characterized by drag and flexures events. This fault divides into smaller rotated fault blocks further north (Faleide et al. 1993).

2.2.7 Eastern platform region

This region includes the Finnmark Platform, Loppa High, eastern Bjørnøya Basin and the Hammerfest Basin. The Hammerfest Basin is characterized by two different fault trends, listric faults detached within or above the Permian succession in the center of the basin and steep faults next to the basin edge. In the basin during Late Jurassic to Early Cretaceous extensional tectonic events were dominant along with slight strike-slip movements (Berglund et al. 1986, Sund et al. 1986, Gabrielsen and Faerseth 1988, 1989). During Middle Jurassic to Early Cretaceous rifting a gentle dome developed parallel to the basin axis which later on finished due to the end of rifting in Early Barremian times (Faleide et al. 1993) (Figure 2.1).

2.3 Stratigraphy

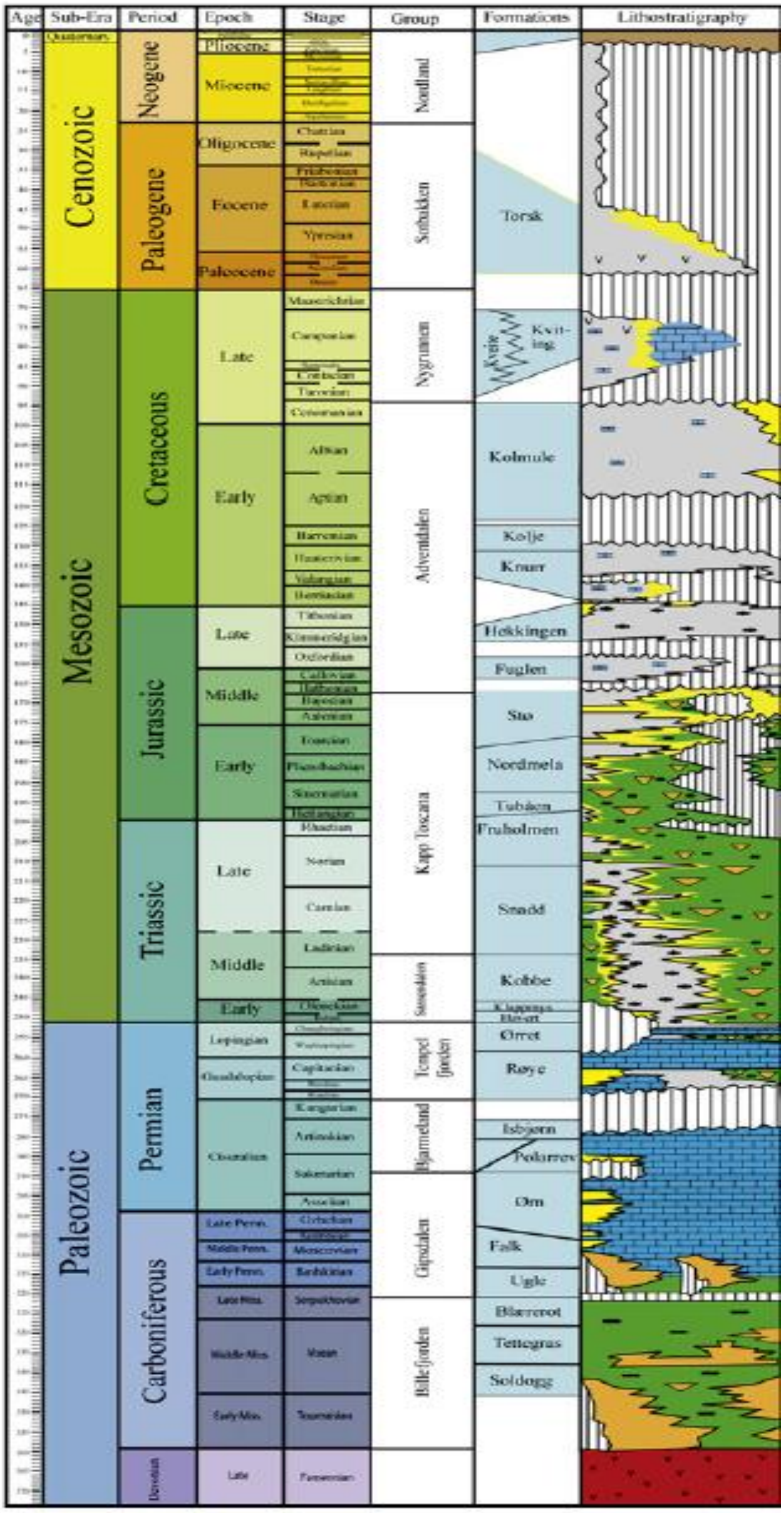


Figure 2.2: Lithostratigraphy of the western Barents Sea (Glørstad-Clark et al. 2010).

2.3.1 Pre-middle Jurassic

On the basis of well information Permo-Carboniferous rocks are mapable in the entire Barents Sea. These rocks are likely to be similar to those of Svalbard, Bjørnøya and NE Greenland (Stemmerik and Worsley 1989). Massive Triassic strata is present throughout the Barents Sea, it shows coarsening upward sequences thus representing transgressions and regressions (Mørk et al. 1989). Sandstone is the dominant lithology in the middle lower Jurassic part which is present allover in the Hammerfest Basin and its thickness is increasing towards the Tromsø Basin. Also these sediments are present in the Finnmark Platform along with Loppa High, however these sediments were moderately eroded due to tectonic activity at some later stage. In the Hammerfest Basin these sandstones represent the major reservoir (Olaussen et al. 1984, Berglund et al. 1986, Grung Olsen and Hanssen 1987, Faleide et al. 1993) (Figure 2.2).

2.3.2 Middle-Upper Jurassic

Teistengrunnen Group is bounded by key unconformities, and the age of these unconformities ranges from Callovian to late Berriasian. The start of rifting in the SW Barents Sea is indicated by the Late Middle Jurassic reflector which is the basal unconformity. On the other hand unconformities present in this group represent interaction between sea level change and Late Jurassic tectonic events. The thickness of the group is minor due to which it is almost impossible to interpret these unconformities on the seismic data. Lithology is dolomitic limestone and few siltstone or sandstone, are interbedded with in shales and claystones. This situation represents calm and deep water settings (Worsley et al. 1988, Faleide et al. 1993) (Figure 2.2).

2.3.3 Lower Cretaceous

The Nordvestbanken Group consists of three formations from the Valanginian to the Cenomanian. To the north and south the group becomes thick before it onlaps against the Loppa High and Finnmark Platform. Main lithology is claystones and shales that have thin interbedded dolomite, siltstone and limestone (Faleide et al. 1993) (Figure 2.2).

2.3.4 Upper Cretaceous

A thin Upper Cretaceous succession shows dominant salt related subsidence and structuring during Late Cretaceous times in the Sørvestsnaget and Tromsø basins. It has been observed that the Nygrunnen Group shows a variation in thickness in the Tromsø Basin. In Tromsø Basin and western part of Hammerfest Basin the lithology is thin limestone along with claystones that transform into sandy succession on the eastern side (Worsley et al. 1988, Faleide et al. 1993) (Figure 2.2).

2.3.5 Palaeogene

The Sotbakken Group and Nygrunnen Group have unconformable contact. This Cretaceous-Tertiary unconformity represents a major break in deposition and is present all over the SW Barents Sea (Worsley et al. 1988). Lithology of the Palaeogene succession is dominated by interbedded siltstones, claystones, carbonates and tuffs (Faleide et al. 1993) (Figure 2.2).

2.3.6 Neogene-Quaternary

The Nordland Group that is of Neogene and Quaternary age lies unconformably on the Paleogene and Mesozoic rocks. The analysis of wells in the Senja Ridge area shows that it has glacial origin (Eidvin and Riis, 1989). Also that the sediments that are about 100-200 m thick in Hammerfest Basin, show great thickness contrast at the Senja Ridge where they have thickness more than 700 m. Further in Lofoten Basin, these sediments extend up to 4000 m (Faleide et al. 1996) (Figure 2.2).

2.4 The study area

The study area for this thesis work is the western part of the Måsøy Fault Complex. It is one of the basin margin faults located in the SW of the Nordkapp Basin and represents the structural separation between the Nordkapp Basin and Finnmark Platform. The fault zone is an extensional structure. The major fault trend in the area is NE-SW, indicating en echelon trend and are associated with major dip slip elements. There are few traces of local compressional events. There is significant flexuring along the fault zone due to the asymmetric subsidence of Nordkapp Basin. The age of the main fault activity is recommended to be Early Carboniferous (Gabrielsen et al. 1990) (Figure 2.3).

The zones of weakness in the basement are associated with the Caledonian Orogeny (Gudlaugsson et al. 1998). These comments may describe the idea of Gabrielsen et al. (1990) that under the Måsøy Fault Complex there are deep rooted faults that are possibly originated from the basement (Ritzmann & Faleide 2007).

The Måsøy Fault Complex was considered to be a part of Troms-Finnmark Fault Complex (Gabrielsen et al. 1984) but further studies in the area showed that there is not any association between these structures. The subsidence was initiated before Permian times. The hanging wall of the major fault in the area is reported to be severely damaged and may indicate inversion (Gabrielsen & Faerseth 1989).

The Måsøy Fault Complex is partly affected by halokinesis (Gabrielsen et al. 1990). This can be explained by the association of Måsøy Fault Complex with the Nordkapp Basin, which is characterized by massive salt deposits.

The SW part of the Nordkapp Basin was created due to the Carboniferous rifting in which Caledonian structures were reactivated (Johansen et al. 1993 & Gudlaugsson et al. 1998). During Late Jurassic to Early Cretaceous and Tertiary there was an episodic reactivation of Carboniferous faults as the basin subsided due to the extension (Gabrielsen et al. 1990). During Late Carboniferous rifting was reduced, further movements were associated with basin marginal faults. The slip along the deep rooted faults caused the deformation of overburden rocks, no matter what their position was with respect to the deep rooted faults. In the Nordkapp Basin the extensional faults present in the younger sediments are associated with the reactivation of deep rooted faults present along the basin margins (Koyi et al. 1993).

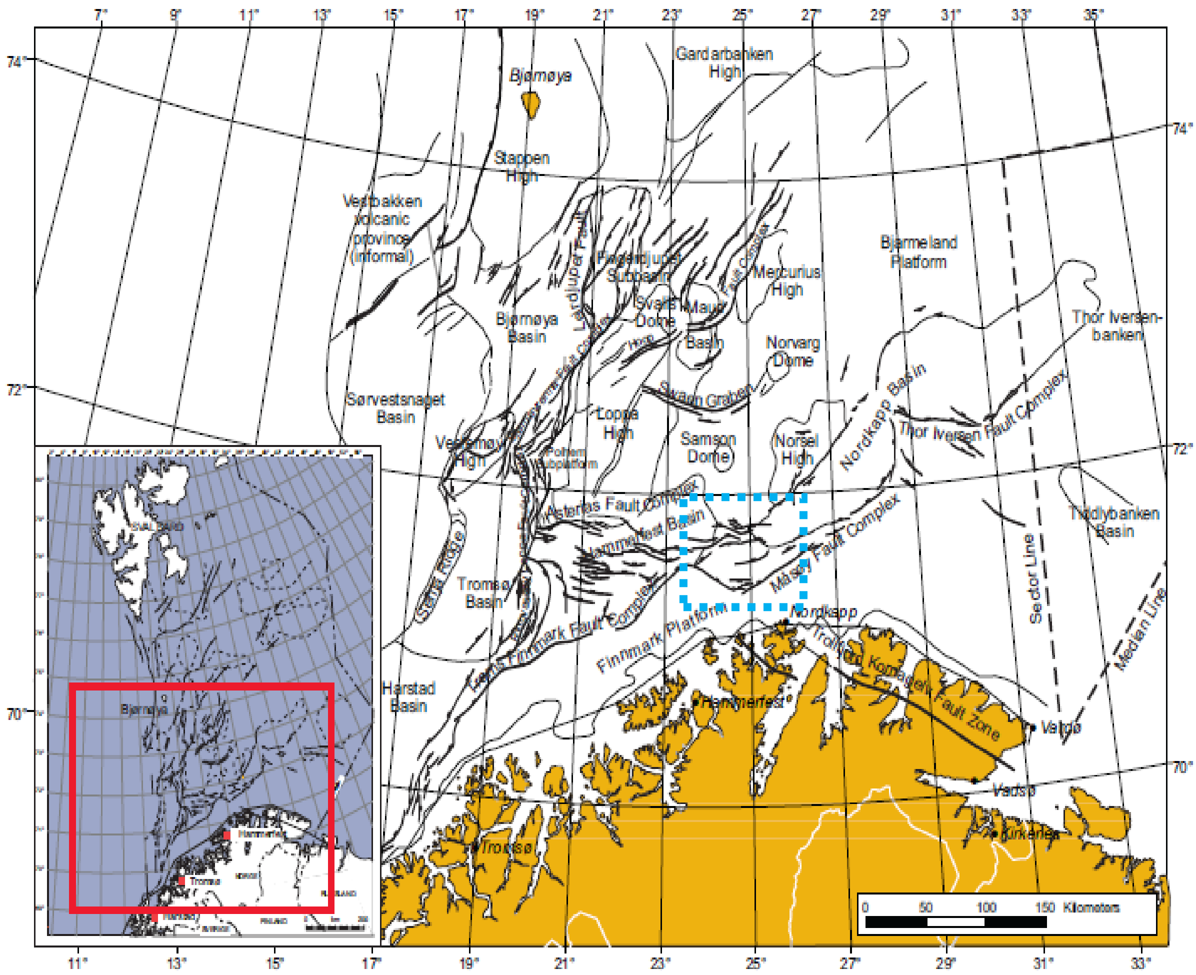


Figure 2.3: The study area (indicated by blue dotted box) along with main structural elements of the Barents Sea (Modified from Larsen et al. 2002).

3 Data and method

Following are the data sets that have been used for this thesis.

1. Regional 2D seismic data.
2. 3D seismic data.
3. Data from three different wells.

3.1 Seismic data

Seismic data include regional 2D lines and 3D survey. Data from four different surveys have been used including three 2D surveys and one 3D survey which is MFZ02 (figure 3.1). On 2D surveys data recording is up to 8 sec (TWT), whereas on MFZ02 which is a 3D survey it is up to 4 s (TWT). It means that the extent of 2D seismic surveys is greater than the 3D.

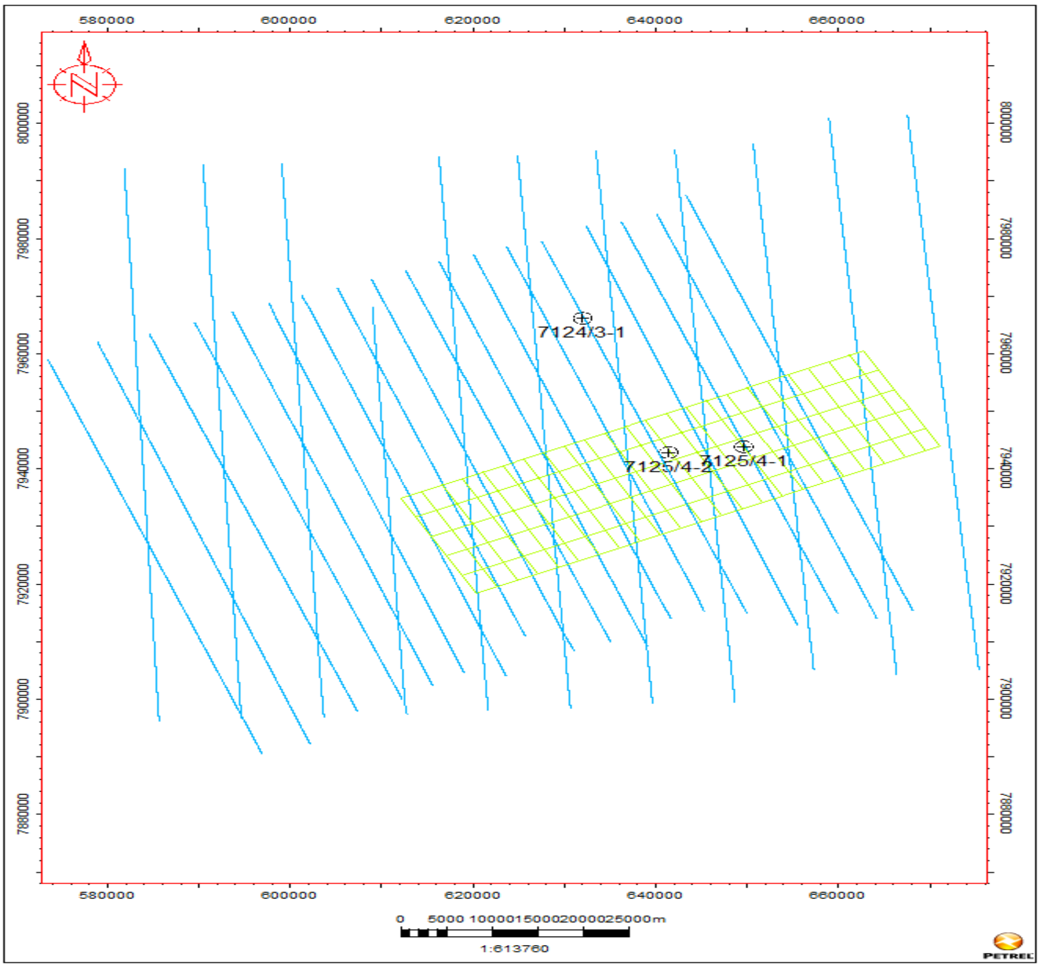


Figure 3.1: 2D/3D seismic surveys along with well locations (for location of study area see Figure 2.3).

3.2 Well data

Data from three different wells have been used. The wells are 7125/4 -1, 7125/4-2 and 7124/3-1 (Figure 3.1). All of the wells are present within the extent of seismic data.

3.2.1 Well 7125/4-1

A wildcat well that was drilled in the area of Måsøy Fault Complex located in the Barents Sea. The main purpose was to look for the commercial hydrocarbons within the Nucula prospect, which represents a fault related structural trap. The structure contains reservoir within the Middle Jurassic to Late Triassic Realgrunnen Group, and Late to Middle Triassic Snadd Formation and the Middle Triassic Kobbe (www.npd.no) (Table 3.1).

3.2.2 Well 7125/4-2

This well was drilled in the area of Måsøy Fault Complex located in the Barents Sea. The purpose of this well was to look for oil and gas, and the target was B segment of Nucula Prospect. Primary target was Kapp Toscana Group sands having age from Late Triassic to Middle Jurassic and the secondary target was lower Kobbe Formation of Middle Triassic (www.npd.no) (Table 3.1).

3.2.3 Well 7124/3-1

This well is located on the eastern side of Hammerfest Basin on the Nysleppen Fault Complex. The main purpose was to understand the source rock potential of the Triassic rocks, identification of whole stratigraphy from seabed down to 4500 m and to perform tests on hydrocarbons at two different levels. The reservoir rocks of Middle Jurassic age was the primary target and Late Carboniferous rocks were secondary target (www.npd.no) (Table 3.1).

Table 3.1: Stratigraphic units encountered in different wells along with their depth (for more details see figure 2.2).

Top Depth (m)	7124/3-1	Top Depth (m)	7125/4-2	Top Depth (m)	7125/4-1
296	NORDLAND GP	317	NORDLAND GP	316	NORDLAND GP
406	SOTBAKKEN GP	520	TORSK FM	493	SOTBAKKEN GP
574	NYGRUNNEN GP	523	NYGRUNNEN GP	493	TORSK FM
574	KVEITE FM	523	KVITING FM	499	NYGRUNNEN GP
618	ADVENTDALEN GP	553	ADVENTDALEN GP	499	KVITING FM
618	OLMULE FM	553	KOLMULE FM	538	ADVENTDALEN GP
1220	KOLJE FM	812	KOLJE FM	538	KOLMULE FM
1233	HEKKINGEN FM	844	KNURR FM	699	NO FORMAL NAME
1285	KAPP TOSCANA GP	891	HEKKINGEN FM	702	KOLMULE FM
1285	TUBÅEN FM	930	KAPP TOSCANA GP	733	KOLJE FM
1305	FRUHOLMEN FM	930	FRUHOLMEN	779	KNURR FM

			FM		
1438	SNADD FM	1026	SNADD FM	817	KRILL MBR
1893	SASSENDALEN GP	1299	SASSENDALEN GP	817	HEKKINGEN FM
1893	KOBBE FM	1299	KOBBE FM	864	ALGE MBR
2334	KLAPPMYSS FM	1683	KLAPPMYSS FM	869	FUGLEN FM
2671	HAVERT FM			872	KAPP TOSCANA GP
3475	TEMPELFJORDEN GP			872	NORDMELA FM
3475	ØRRET FM			882	FRUHOLMEN FM
3670	RØYE FM			1002	SNADD FM
3900	ULV FM			1206	SASSENDALEN GP
3952	BJARMELAND GP			1206	KOBBE FM
3952	ISBJØRN FM			1561	KLAPPMYSS FM
4000	POLARREV FM				
4271	GIPSDALEN GP				

3.3 Method

Petrel has been used for this thesis. This software is window based and is assets of Schlumberger. Petrel can perform various operations, including interpretation of seismic data, well correlation, can generate reservoir models, calculation of volumes etc. For this thesis work petrel version 2009 has been used. Following are the features of petrel that are used during the work (www.slb.com).

3.3.1 Data import

This process involves the loading of data in to the software. That includes well data and 2D / 3D seismic data which is loaded in SEG-Y format. For the import of well data first step is to insert a new well. Then to give coordinates for the particular well along with the kelly bushing value. To enter well tops, well tops folder has to be generated. Further well tops can be imported to the database. Similarly check shot data can be imported into the data base.
For loading of the 2D / 3D seismic data initially new seismic main folder has to be generated using insert option. Then a subfolder has to be generated named as seismic survey. And finally all kind of seismic data can be stored into the software as a SEG-Y format.

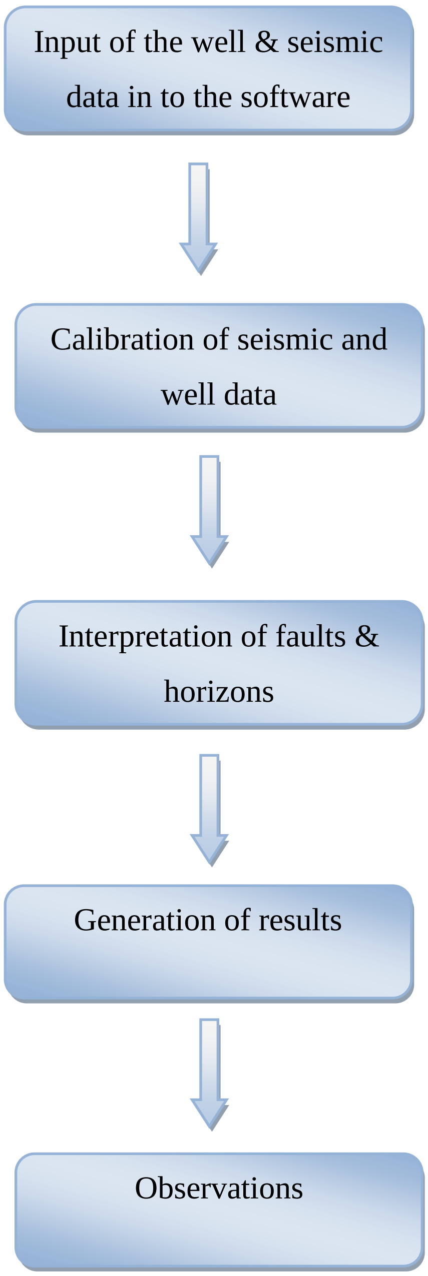
3.3.2 Seismic interpretation

Before starting the seismic interpretation process it is necessary to do seismic to well tie. This is important because on the basis of this step interpretation of a certain horizon can be carried out. Seismic interpretation can be performed on any kind of seismic line. That can be simply 2D line, inline, cross line etc. There are two kinds of windows which are used to perform seismic interpretation. These are 3D window and Interpretation window. But it is recommended that interpretation should be carried out by using Interpretation window. However 3D window can be used for the 3D view of different results regarding interpretation. Horizons can be interpreted by four different ways. These are

- Guided auto tracking
- Seeded 2D auto tracking
- Seeded 3D auto tracking
- Manual interpretation

3.3.3 Map generation

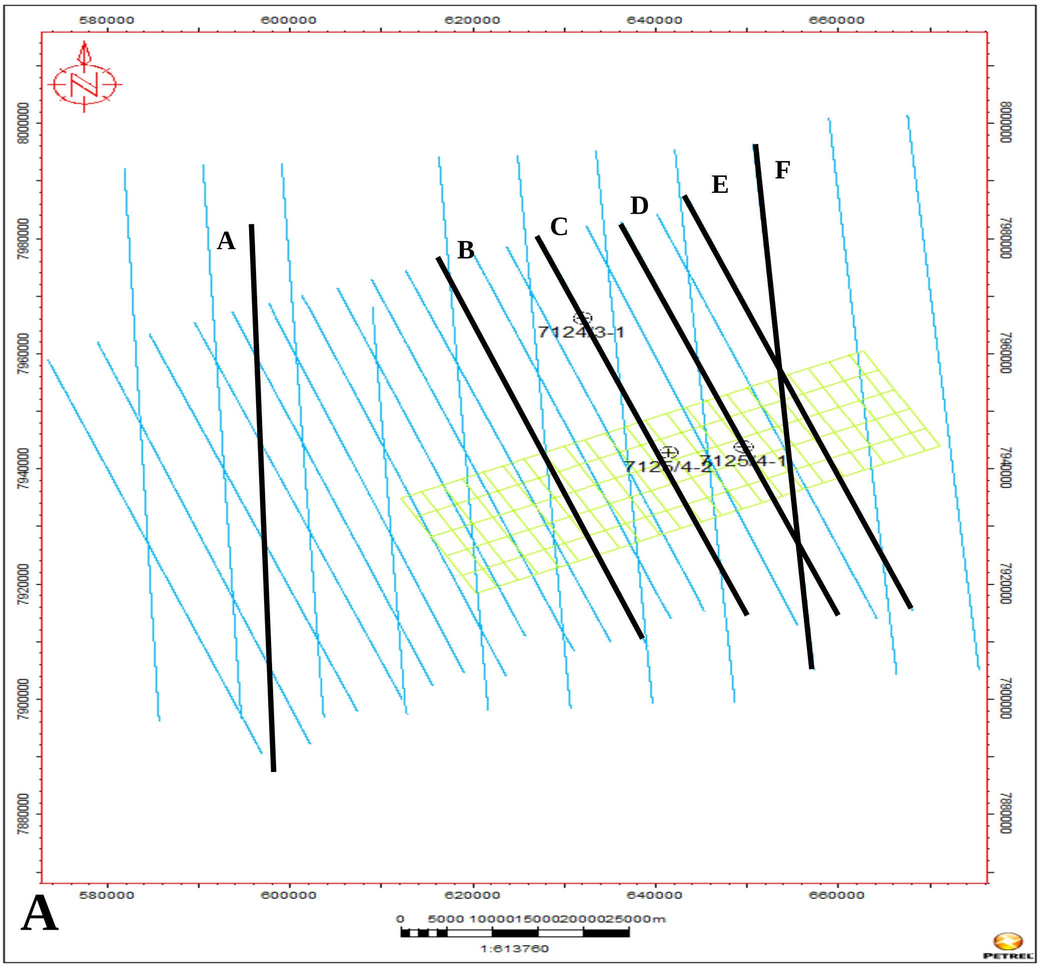
Different maps can be generated after the interpretation of all kind of seismic data. These maps can be time structure map, time thickness map etc. Maps can be viewed in 3D window, 2D window and Map window. These maps are generated in order to understand the interpretation results in terms of stratagraphy and tectonics. After the complete interpretation of certain horizon the result of that horizon is used as an input to Make/edit surface process. And finally result of that certain horizon can be viewed in desired window. The procedure for seismic interpretation can be explained by following flow chart.



4 Seismic interpretation

4.1 Seismic to well tie

As stated before, data from three wells have been used. Well 7124/3-1 is lying on seismic line C and well 7125/4-1 is present on seismic line D. Well 7125/4-2 is situated in between both of these lines. The distance of this well from seismic line D is 8267 m (approx) and from C the distance is 544 m (approx). Wells 7125/4-1 and 7125/4-2 are lying within 2D/3D seismic survey however 7124/3-1 is bit away from 3D survey that is 10954 m (approx) (Figures 4.1, 4.2, 4.3).



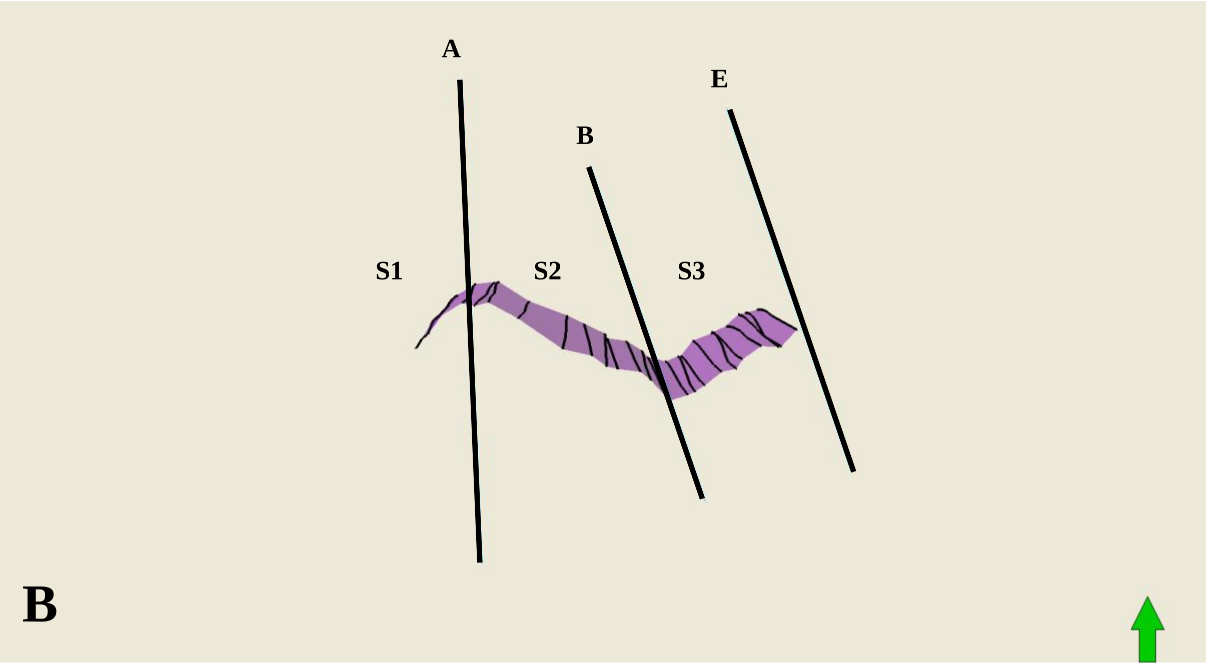


Figure 4.1: A: 2D/3D data coverage, B: Orientation of the major fault (F1).

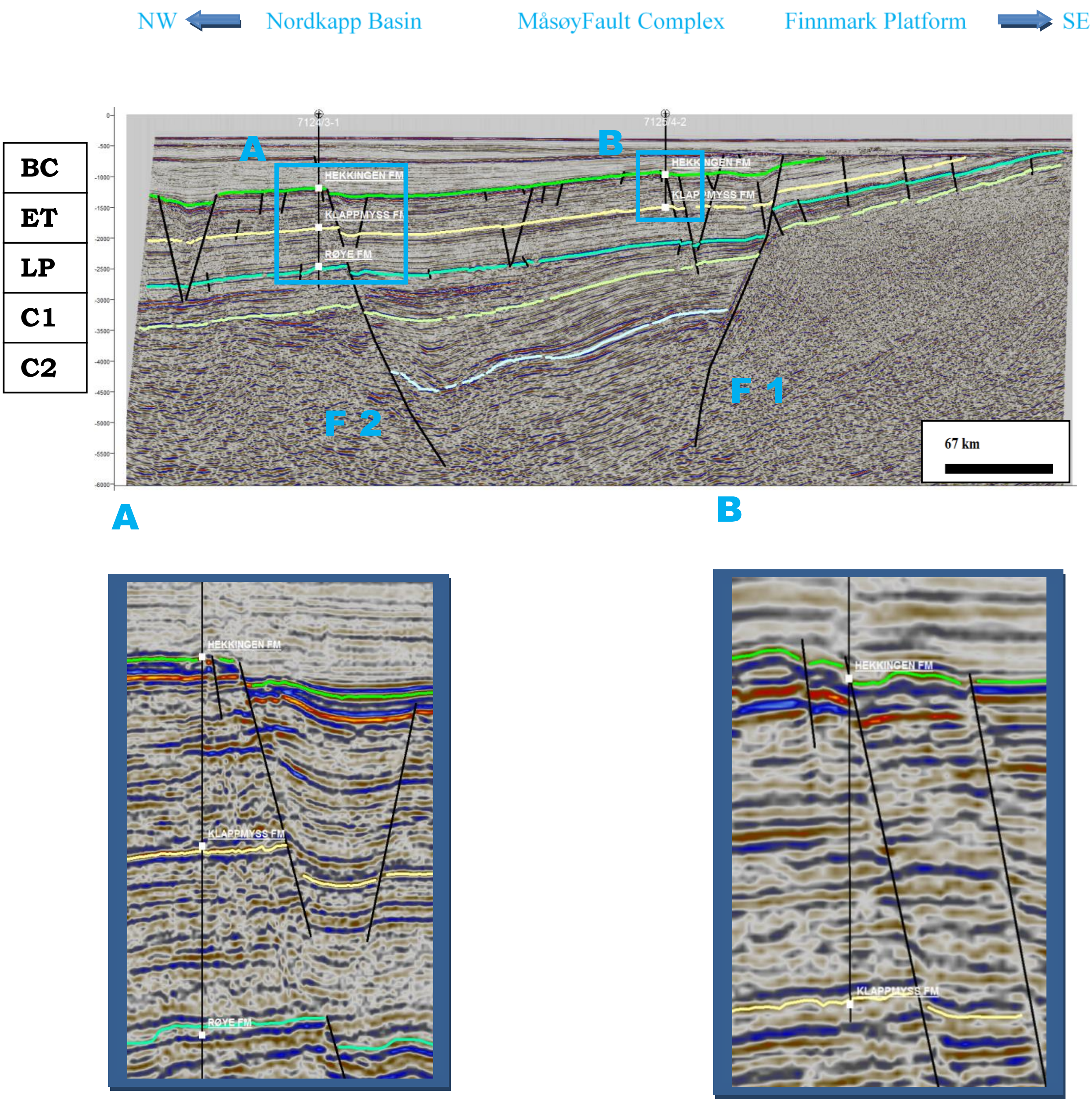


Figure 4.2: Seismic line C showing seismic to well tie (A: 7124/3-1, B: 7125/4-2) (further details in section 4.2, see Figure 4.1 for location and Table 4.1 for age of interpreted horizons).

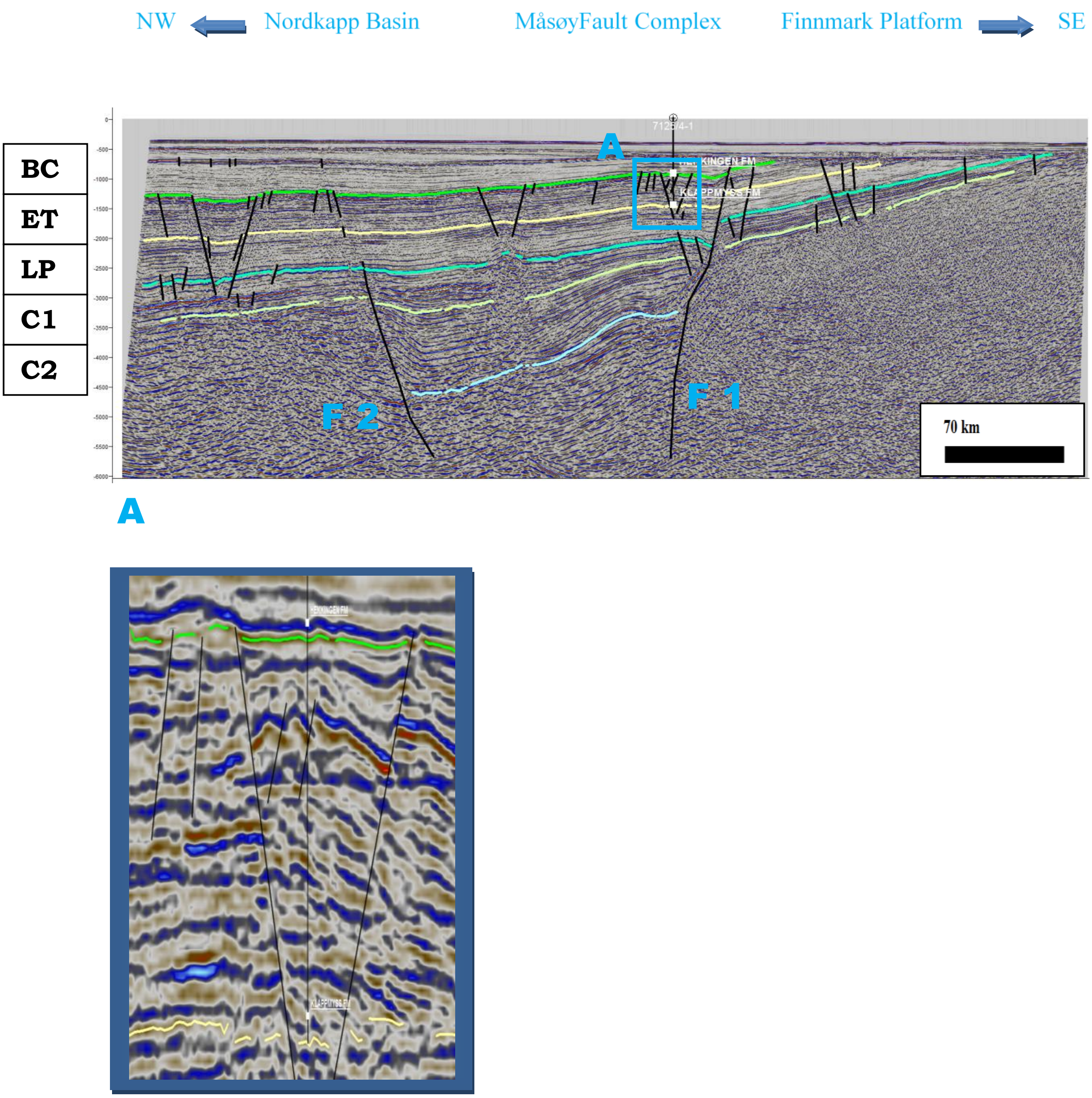


Figure 4.3: Seismic line D showing seismic to well tie (A: 7125/4-1) (further details in section 4.2, see Figure 4.1 for location and Table 4.1 for age of interpreted horizons).

4.2 Selected seismic reflections

There are five horizons that are interpreted on the seismic data. For three horizons there is a proper well control, these are top Hekkingen Formation, top Klappmyss Formation and top Røye Formation. In case of Carboniferous two horizons have been interpreted on the basis of high amplitude reflection and their continuation. This is because the maximum depth of the wells that are used is down to Early Permian only (Figures 4.2, 4.3), (Table 4.1).

Table 4.1: Details for interpreted horizons.

Horizons	Formation Name	Age	Color
BC	Hekkingen Fm	Base Cretaceous	
ET	Klappmyss Fm	Early Triassic	
LP	Røye Fm	Late Permian	
C1	----------------	Late Carboniferous	
C2	----------------	Early Carboniferous	

4.2.1 C2

On seismic data it can be interpreted between 3000 ms towards Finnmark Platform and 4500 ms towards Nordkapp Basin. In terms of amplitude and continuity it is totally opposite to the rest of horizons. It is extremely chaotic and at places it is even difficult to interpret particularly on 2D data. However on 3D data it's easy to interpret. Since this horizon is very deep its chaotic nature can be the result of low frequencies. Where ever there are high frequencies the resolution is also high. Similarly if the frequencies are low the resolution is also less. With the increase in depth higher frequencies are attenuated and only low frequencies are left resulting in less resolution of seismic data. Hence there is a possibility that low frequencies affected this horizon in terms of resolution (Figures 4.4, 4.5).

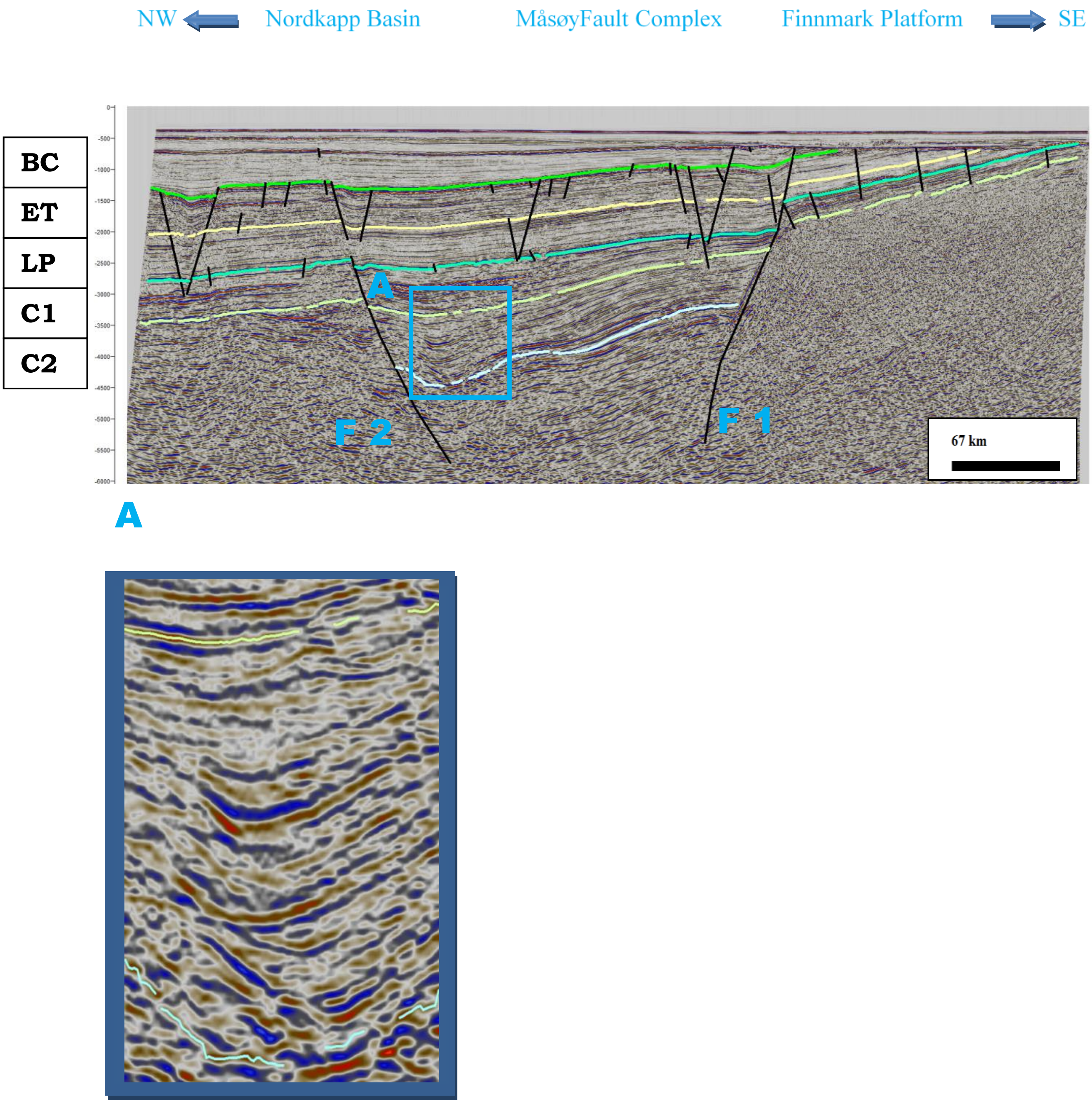


Figure 4.4: 2D seismic line C (A: Amplitude variations between C1 and C2) (See Figure 4.1 for location and Table 4.1 for age of interpreted horizons).

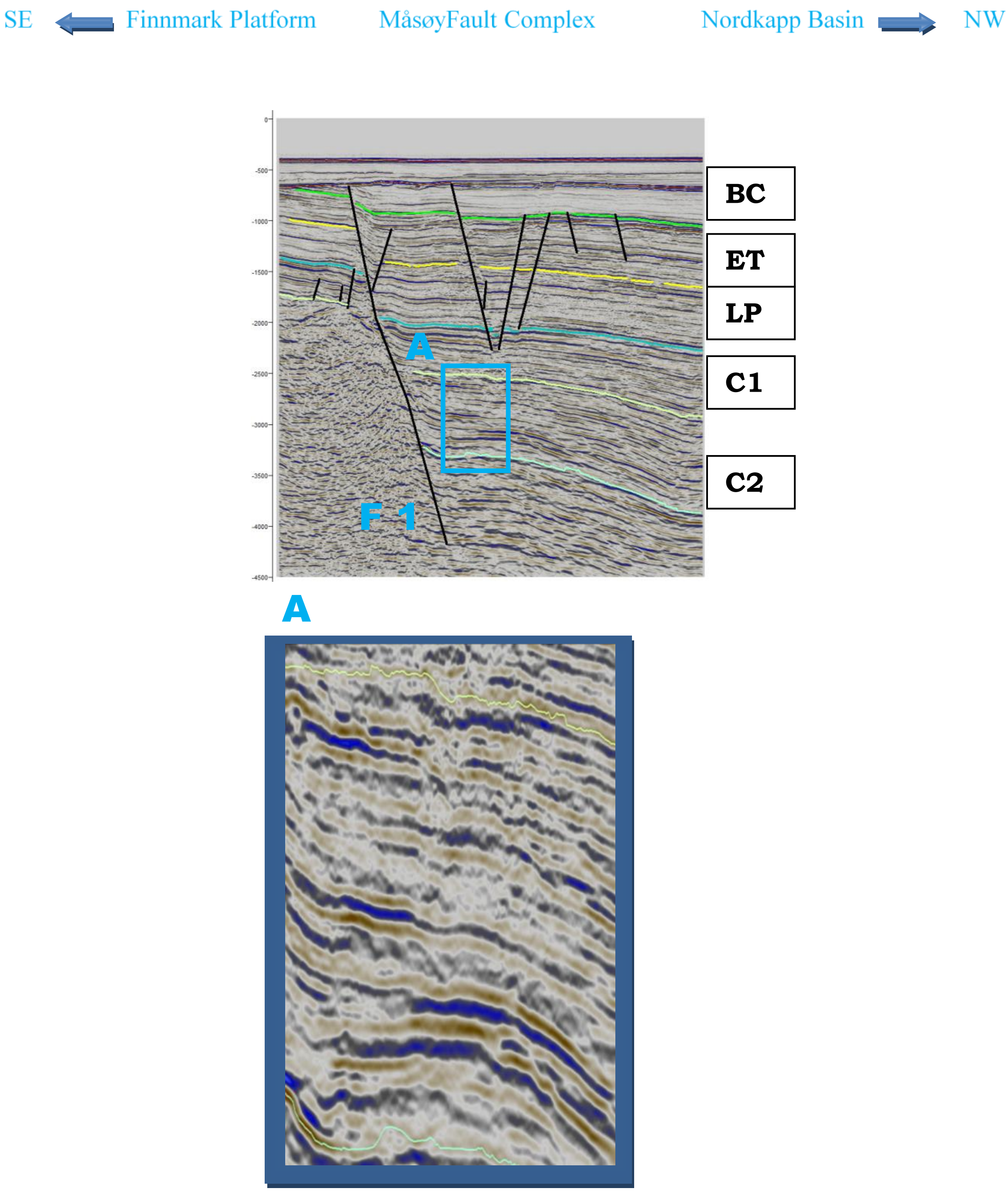


Figure 4.5: 3D random line (A: Amplitude variations between C1 and C2) (See Table 4.1 for age and interpreted horizon).

4.2.2 C1

Like C2 the interpretation has been carried out on the basis of high amplitude and continuity of the reflections at Late Carboniferous level. On seismic data it has been interpreted between 750 ms towards Finnmark Platform and 3500 ms towards Nordkapp Basin. It is characterized by medium to high frequency. It has a very chaotic nature and at places it is very hard to interpret on 2D seismic data particularly on the footwall. However on 3D data the reflections are easy to interpret at this level. This horizon has not been eroded (Figures 4.4, 4.5).

4.2.3 LP

LP horizon has been penetrated by only one well which is 7124/3-1. On seismic data it can be interpreted between 600 ms towards Finmark Platform and 2800 ms towards Nordkapp Basin. Characterize by high frequency. At some places polarity reverse event can also be observed. Fair amplitude on both of the data sets 2D and 3D. On the foot wall of the major fault (F1), towards Finmark Platform it is truncated by Base Tertiary strata (Figures 4.6, 4.7).

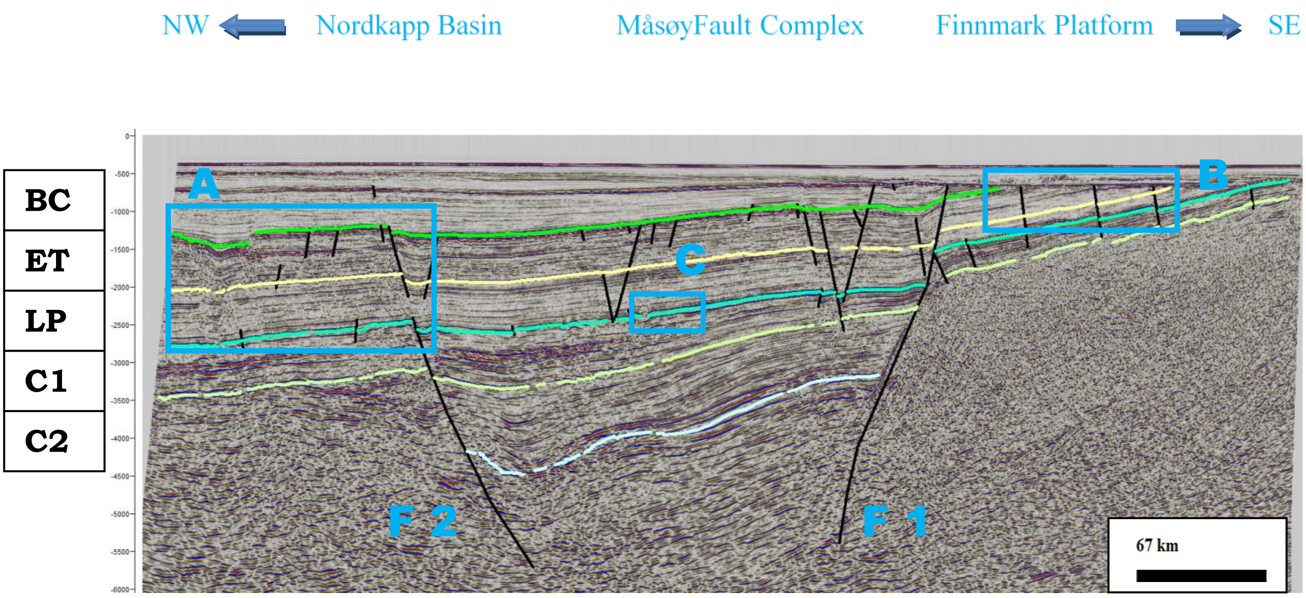


Figure 4.6: 2D seismic line C (A: Amplitude variation between LP, ET and BC, B: Erosional truncation, C: Example for polarity reverse) (See Figure 4.1 for location and Table 4.1 for age of interpreted horizons) (details on next page)

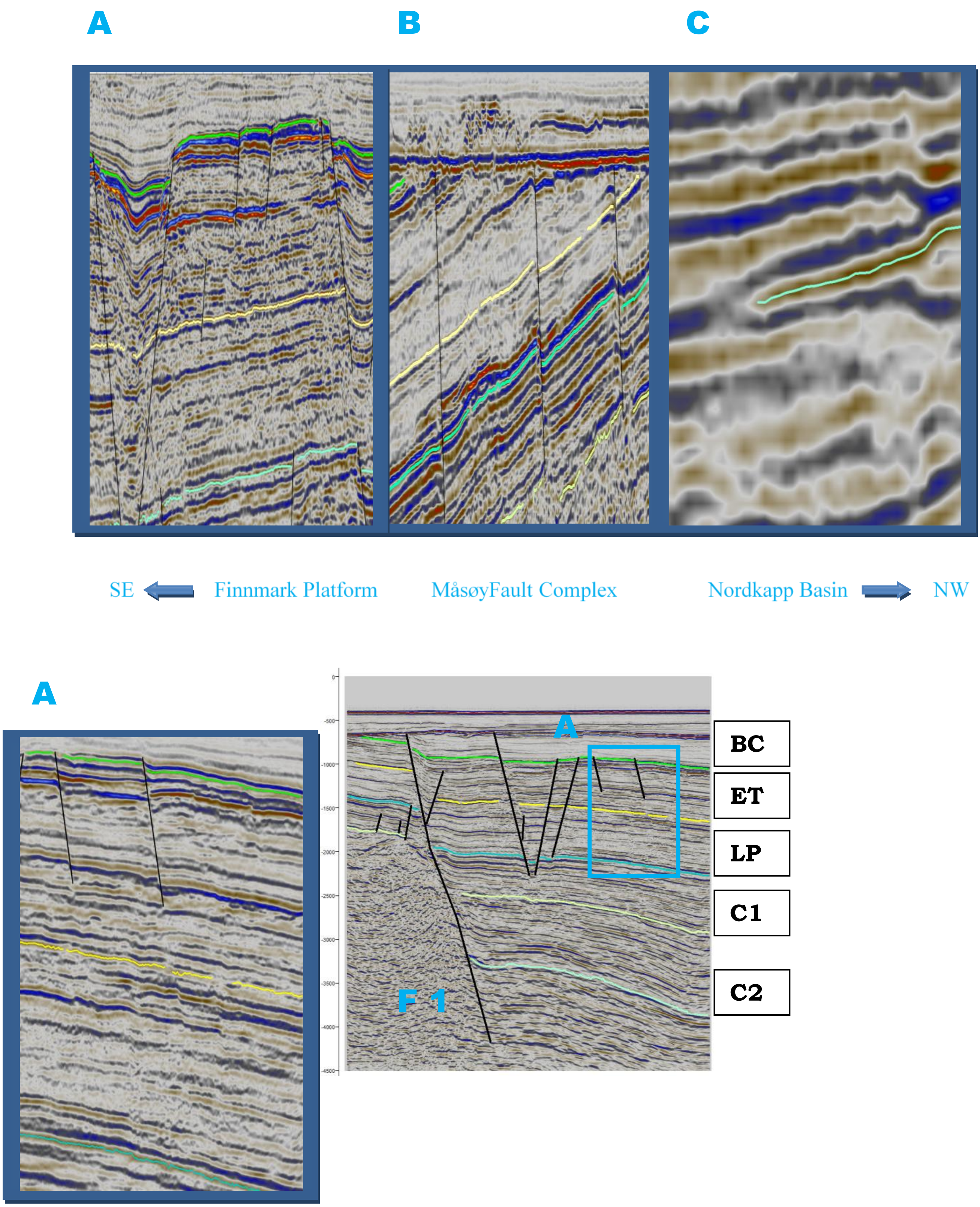


Figure 4.7: 3D random line (A: Amplitude variation between LP, ET and BC) (See Table 4.1 for age and interpreted horizons).

4.2.4 ET

It has been penetrated by all of the wells. ET is the last horizon encountered in wells 7125/4-1 and 7125/4-2. On seismic data it can be interpreted between 650 ms towards Finnmark Platform and 2100 ms towards Nordkapp Basin. ET has strong amplitude on both 2D and 3D data sets along with high frequency. Towards the Finmark Platform amplitude is a bit low but still it can be easily interpreted. Although it has been cut by many faults still it is continuous on both of the data sets. On the hanging wall side of the major fault (F1) the formation is affected by erosion and it is truncated by Base Tertiary sediments. At places there are chaotic reflections along with polarity reverse features. This can be the effect of fault activity and lithology variations within the formation (Figures 4.6, 4.7).

4.2.5 BC

BC has been penetrated by all of the three wells. On seismic data it can be interpreted between 600 ms towards Finmark Platform and 1400 ms towards Nordkapp Basin. At some places polarity reverse event can also be observed. It has high amplitude and frequency on both of the data sets 2D and 3D. Towards Nordkapp Basin it is stable in term of amplitude and continuity. However it has a very disturbed amplitude and continuity towards Finnmark Platform where it is mostly absent due to erosion. On the footwall of the major fault (F1), towards Finnmark Platform it is truncated by Base Tertiary sediments (Figures 4.6, 4.7).

4.3 Selected profiles

Following are the seismic lines that are selected on the basis of the orientation of the major fault that is changing from west to east and to point out the structural differences (Figure 4.1).

4.3.1 Seismic line E

This line is located on the eastern termination of major fault (Figure 4.1). The orientation of the line is NW-SE and is orthogonal to the major fault. Major is characterized by high angle. Displacement and the normal throw across the fault at C1, LP and ET levels are greater as compared to the BC level. Towards the hanging wall at C1 level there is a significant reverse drag, whereas rest of the horizons do not show this kind of feature.

Minor faults are abundant at Base Cretaceous, Triassic and Permian levels. Mostly they are positioned on the hanging wall of the major fault. Most of the minor faults are dipping in the same direction as the major fault, while others have an opposite trend with respect to the major fault. F2 is the main antithetic fault in the area. Normal faults are dominant at different levels along with related structures such as graben and horst. F1 and F2 represent the major graben structure in the area. Strata towards the hangingwall of the major fault is much more disturbed as compared to the footwall due to the tectonic activity. Variation in the thickness of sediments across the fault is clear. At Base Cretaceous, Triassic, Permian and C1 levels towards the footwall sediments have less thickness as compared to the hanging wall. This situation indicates that during deposition of sediments the fault was active. Towards the hanging wall at C2 level there is a dome like structure that is developing.

On the basis of interpreted seismic data it is very apparent that the fault has penetrated through the C2 seismic reflection which is Early Carboniferous in age and further continuation of the major fault may suggest that it is approaching to the basement (Figure 4.8).

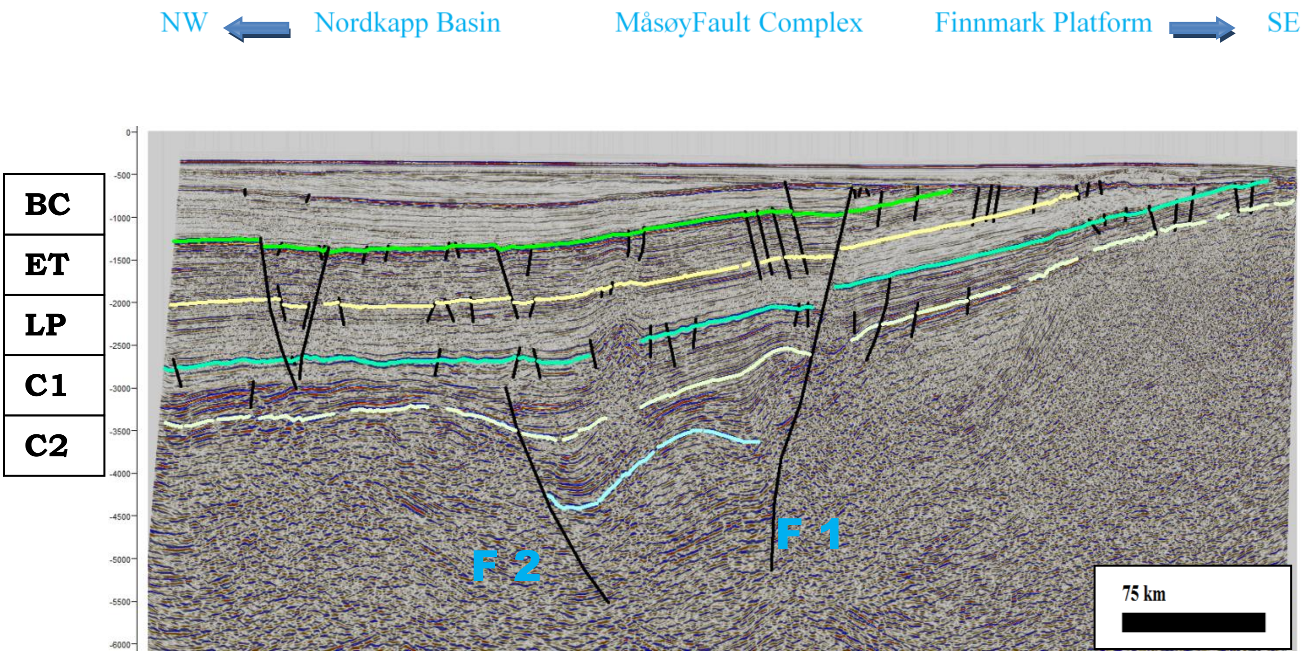


Figure 4.8: Interpreted seismic line E (See Figure 4.1 for location and Table 4.1 for age of interpreted horizons).

4.3.2 Seismic line B

This line is located in between two different strikes of the major fault (Figure 4.1). On the western side of the line strike is NW-SE and on the eastern side the strike is NE-SW. Again major fault (F1) is representing high angle. The trend of the line is NW-SE. Displacement and the throw across the fault at C1, LP and ET levels is greater as compared to the BC level (Figure 4.9). The amount of displacement and throw of the horizons on this line is greater as compared to eastern line E (figure 4.8). Drag features are absent. Again the normal faults at different levels are dominant and most of the faults are having same trend as the major fault. F2 is the major antithetic fault. Both faults F1 and F2 represent a graben structure. The intensity of faulting in the central zone is dominant as compared to the eastern zone of the seismic survey. Once more there is a great variation in the thickness of sediments across the fault. The thickness variation is greater as compared to the eastern part of the survey. This again indicates the activation of fault during deposition of sediments. On the basis of interpreted seismic data it can be concluded that the major fault in the central part of the survey has the same trend as it has in the eastern part. Which is represented by steep dipping, normal fault along with a significant bend (Figure 4.9).

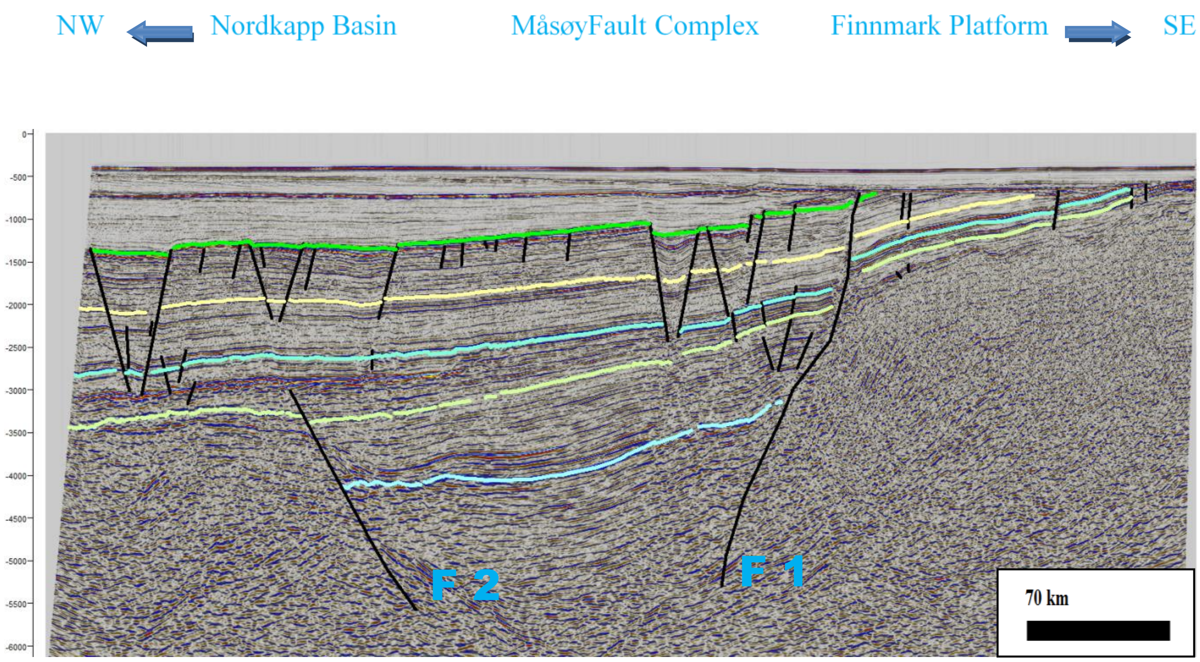


Figure 4.9: Interpreted seismic line B (See Figure 4.1 for location and Table 4.1 for age of interpreted horizons).

4.3.3 Seismic line A

This N-S trending line is located in between two different strikes of the major fault (Figure 4.1). To the west the strike is NE-SW and to the east the strike is NW-SE. Major fault (F1) is characterized by high angle. Displacement and the throw across the fault at C1, LP, ET and BC levels are prominent (figure 4.10). This indicates that the intensity of displacement and the throw across the fault at these levels is very high on the western side of the seismic survey as compared to the eastern and central zones. Towards the hanging wall of the major fault there is a noticeable normal drag at C1, C2, ET and BC levels, whereas at LP level there is a reverse drag. Between LP and ET the drag along the fault is changing from normal to reverse. Across the major fault normal faulting is plentiful with most of the faults having the same dip direction as the major fault. Towards the hanging wall there is significant subsidence indicated by the dip of the strata at different levels. Sediments thickness variation across the fault is greater. This thickness difference across the fault is much greater as compared to the eastern and central zones of the seismic survey. This again is the sign of tectonic activity during deposition. On the basis of above mentioned information it seems that tectonic activity has much more pronounced effect along the major fault on the western side as compared to the eastern and central zones. However rest of the details is similar to the other zones. That the fault is steep, represents normal faulting (Figure 4.10).

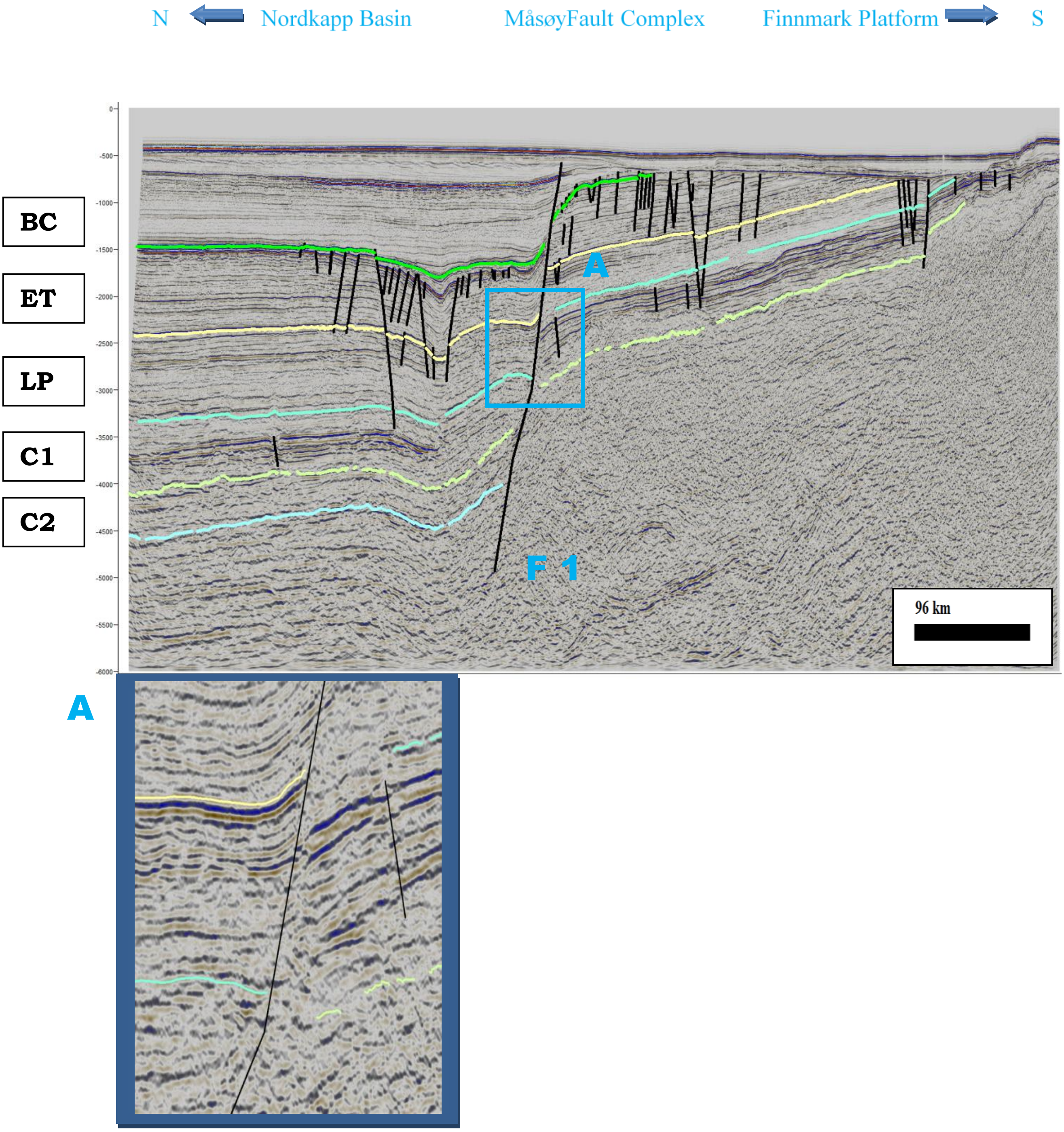


Figure 4.10: Interpreted seismic line A (A: change in drag) (See Figure 4.1 for location and Table 4.1 for age of interpreted horizons).

4.4 Structural maps

Following are the structural maps of interpreted horizons. Time-structure maps were generated using the software, whereas structural trend maps were generated manually on the basis of information extracted from interpreted seismic sections.

4.4.1 C 2

This is the deepest horizon interpreted on the seismic data. It has a limited extent and is bounded by major fault (F1) and F2. The time values show the trend regarding the depth of basin which is increasing northwards (Figure 4.11)

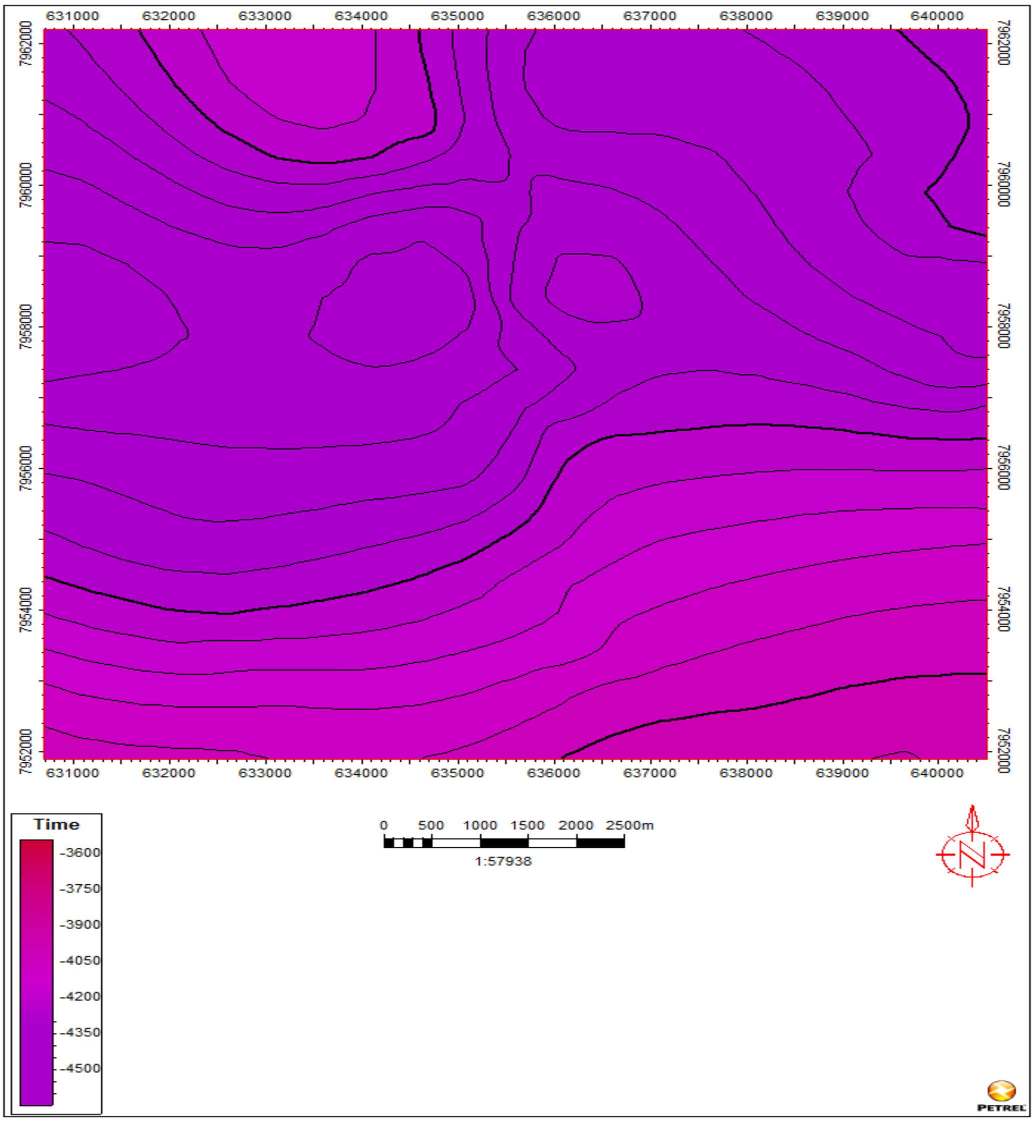


Figure 4.11: Time-structure map, C2.

4.4.2 C 1

The time-structure and fault maps indicates faults with contrasting strikes at this level (Figures 4.12, 4.13). One with NW-SE strike and other is having NE-SW strike. Faults with NE-SW strike are abundant. Two prominent features include the major fault along with a southward dipping fault further north. The throw of the major fault is towards north and is characterized by three different strikes, including SW-NE, NW-SE and SW-NE. The dipping direction of the smaller faults with respect to the major faults indicates their synthetic and antithetic nature. Graben and horst structures on smaller scale are abundant. Most of the faults have the same throw as the major fault. Their placement is parallel to sub parallel with respect to each other. The population of faults at this level towards the Nordkapp Basin indicates that hanging wall of the major fault is structurally more complex as compared to the footwall that is towards Finnmark Platform. Towards south presence of minor tectonic activity indicates that erosional effect due to uplift is absent. Time values indicate northward deepening basin (Figures 4.12).

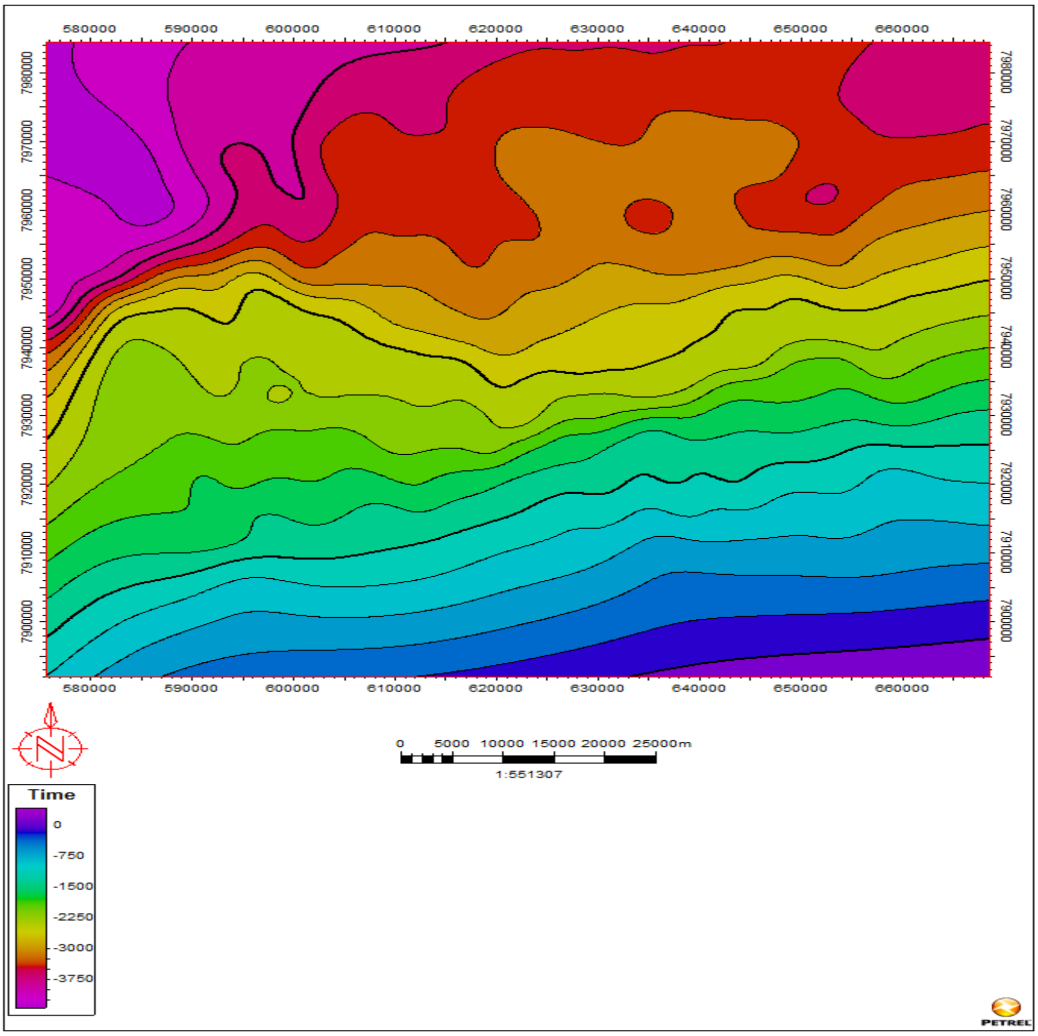


Figure 4.12: Time-structure map, C1.

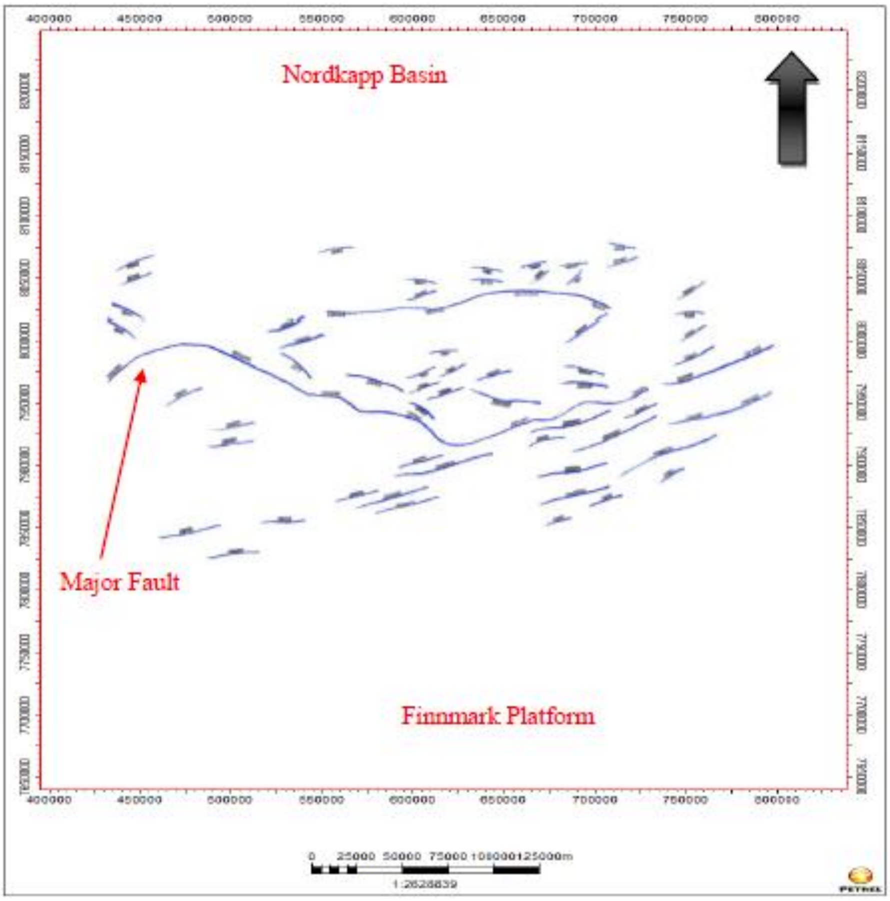


Figure 4.13: Structural trend map, C1.

4.4.3 LP

Along with major fault there are two main structural features that are present at this level (Figures 4.14, 4.15). A graben structure further north which is striking west to east and a fault in between that graben structure and the major fault whose throw is opposite to the major fault, indicating major antithetic fault present at this level. The dominant throw of most of the faults is towards north. Extensional structures including horst and graben are abundant. Majority of the faults are located towards the hanging indicating the pronounced faulting towards north as compared to the south. Presence of structural features towards south indicates that the horizon is mostly continuous, and has not been greatly affected by the erosion. Basin depth indicated by time values (Figure 4.14).

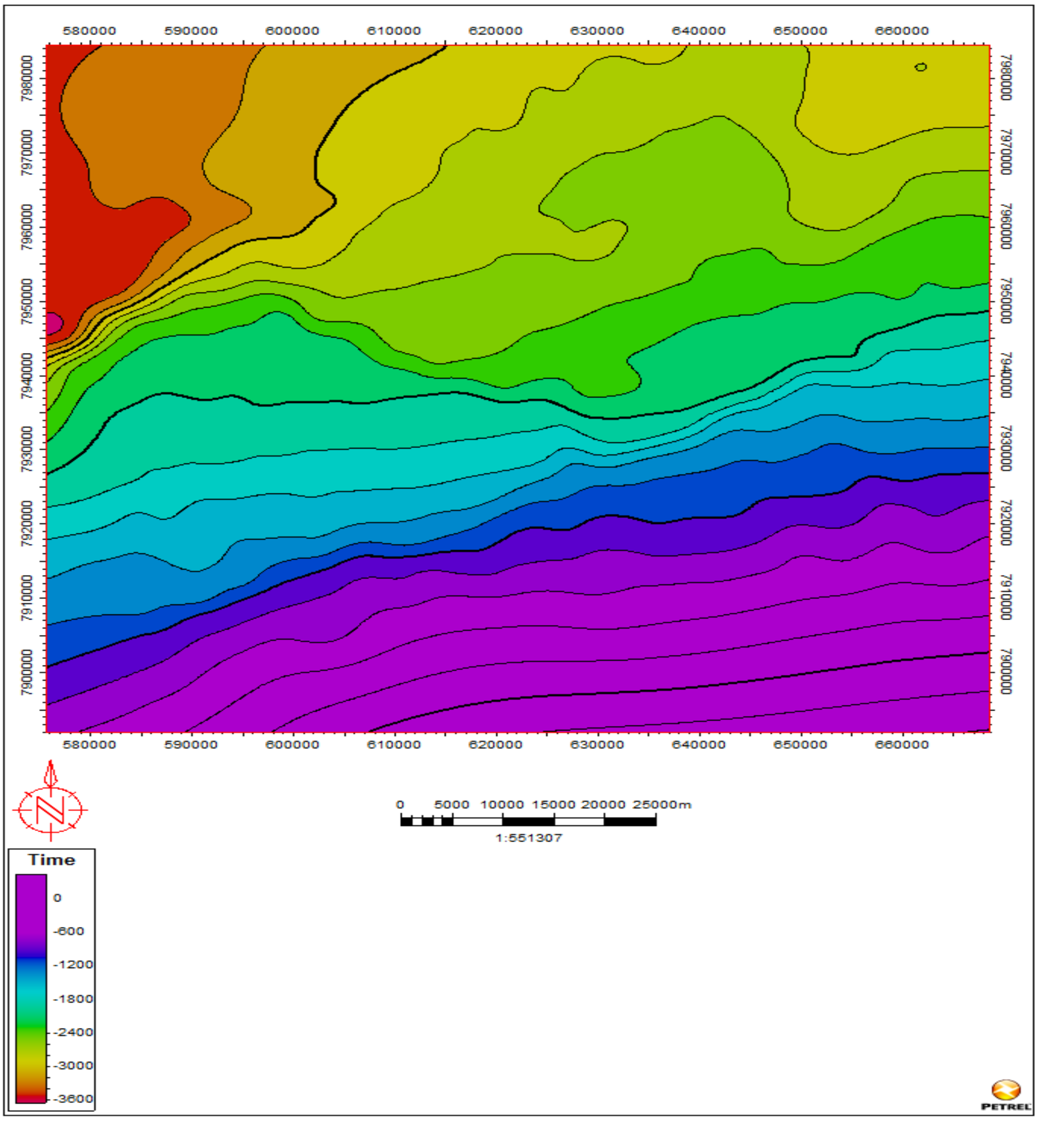


Figure 4.14: Time-structure map, LP.

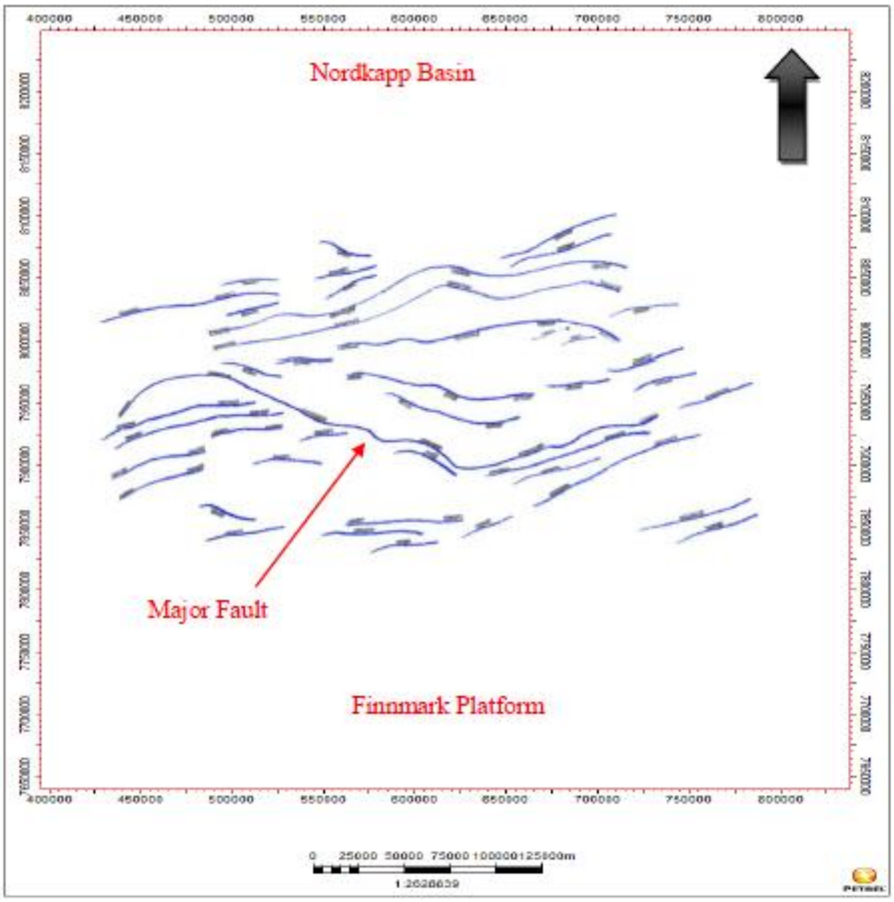


Figure 4.15: Structural trend map, LP.

4.4.4 ET

Major structural elements at this level (Figures 4.16, 4.17) are major fault along with a graben structure further north. Minor faults are abundant along with graben and horst structures that are dominating the area. The dominant trend of the smaller faults is NE-SW with throw direction similar to the major fault. Faults with NW-SE strike are less. Synthetic faults are abundant whereas antithetic faults are less indicated by the throw direction with respect to the major fault. The population of the faults towards the hanging wall of the major fault described the intensity of tectonic events that are dominant towards north. Erosional affects towards south are very obvious due to footwall uplift. Limited tectonic activity indicates that the horizon is not very continuous towards south. Further north sediments are getting deeper indicated by time values (Figures 4.16).

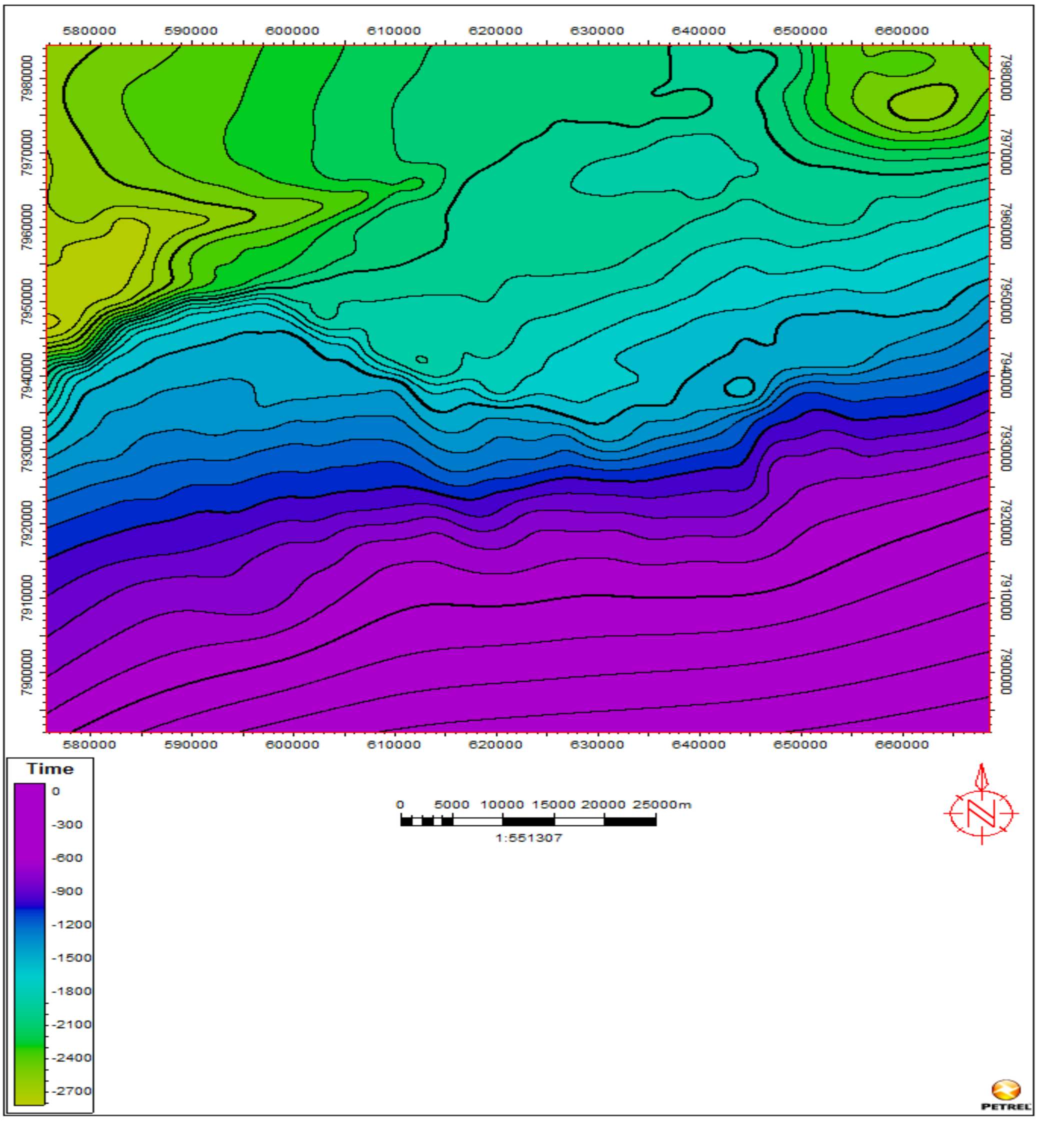


Figure 4.16: Time-structure map, ET.

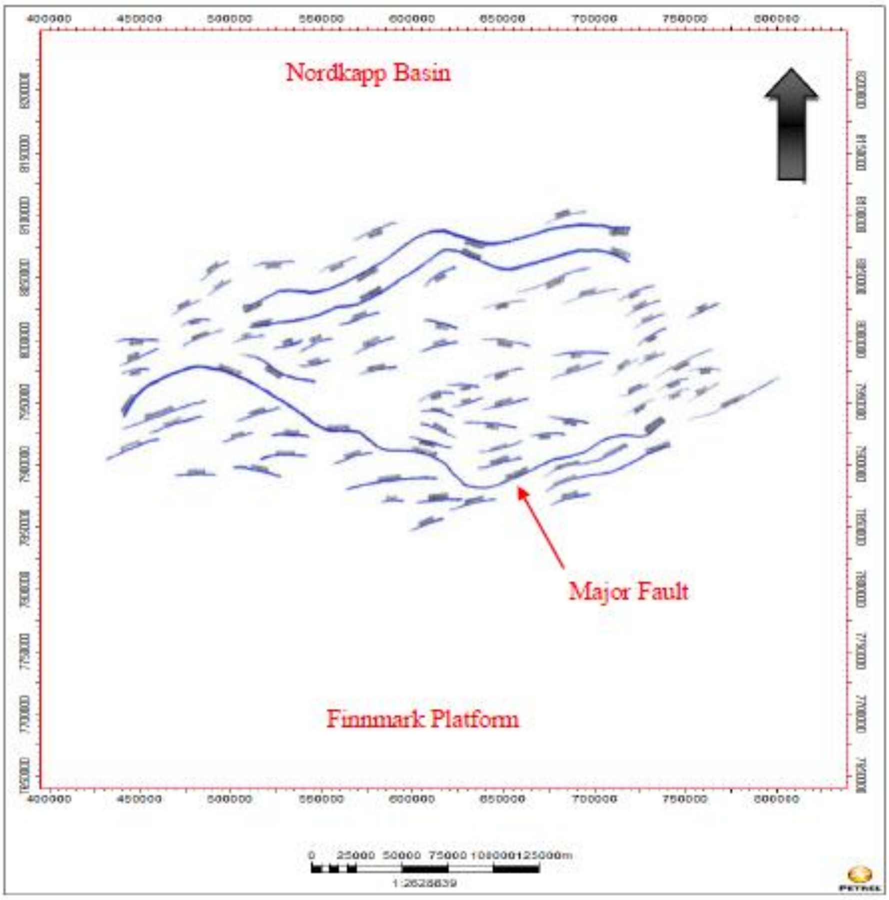


Figure 4.17: Structural trend map, ET.

4.4.5 BC

Perhaps more structurally disturb horizon than rest of the interpreted levels (Figures 4.18, 4.19). The structural map indicates the intensity of faulting that is increasing northwards. Prominent features include major fault with throw towards north and a graben structure. The dominant trend of the smaller faults is same as rest of the horizons which is indicated by NE-SW strike. Graben and horst structures are abundant. Majority of the faults are synthetic indicated by the direction of their throw with respect to the major fault. Positioning of the faults is parallel to sub parallel. Normal faulting is accompanied by reverse faulting at this level. Again the population of the faults is increasing towards the hanging wall of the major fault. Towards the footwall there is an insignificant tectonic activity. This can be explained by the erosional affects due to uplift, as the horizon is mostly missing toward south. Again the time values indicate the north wards increase in sedimentation (Figure 4.18).

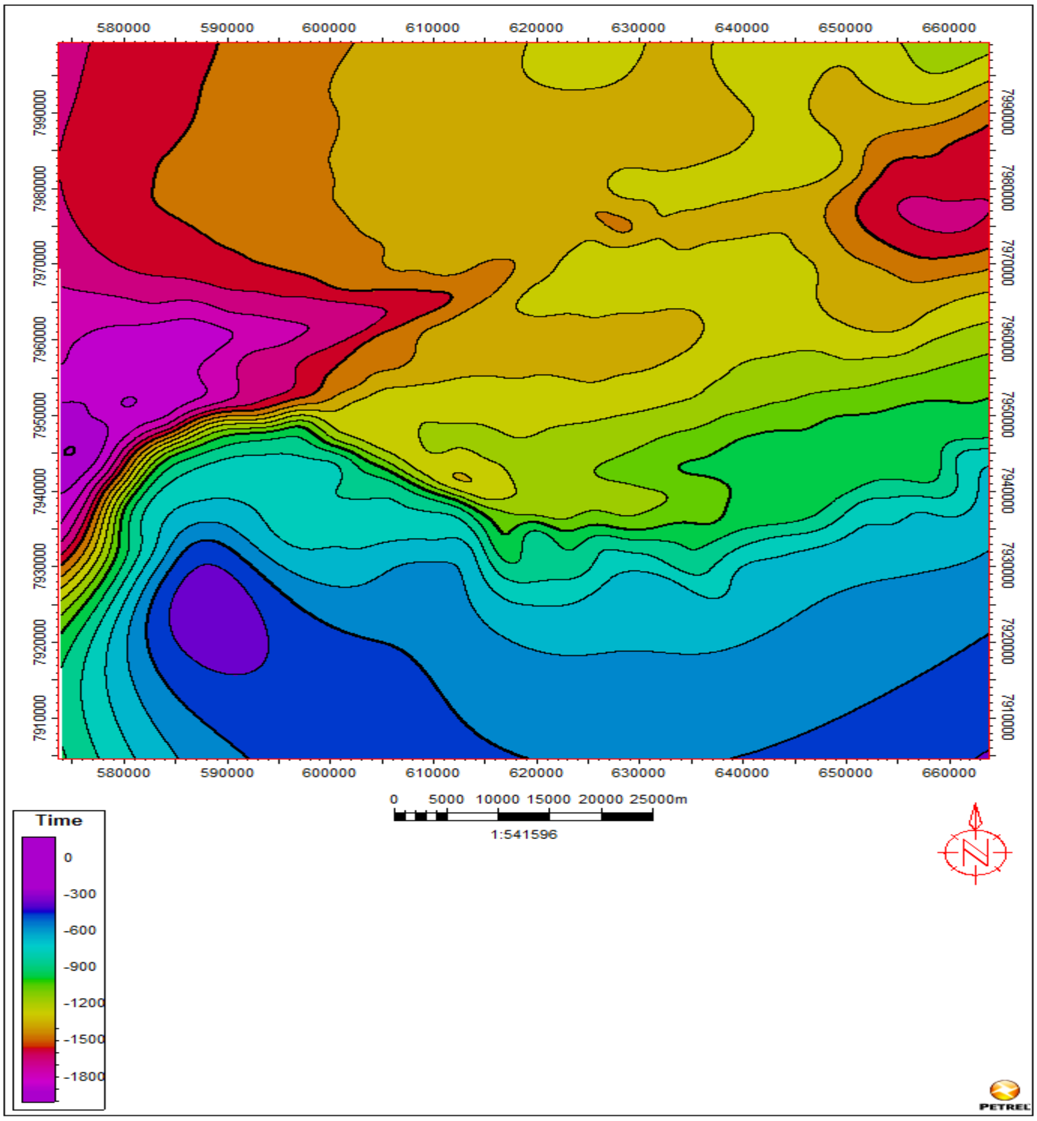


Figure 4.18: Time-structure map, BC.

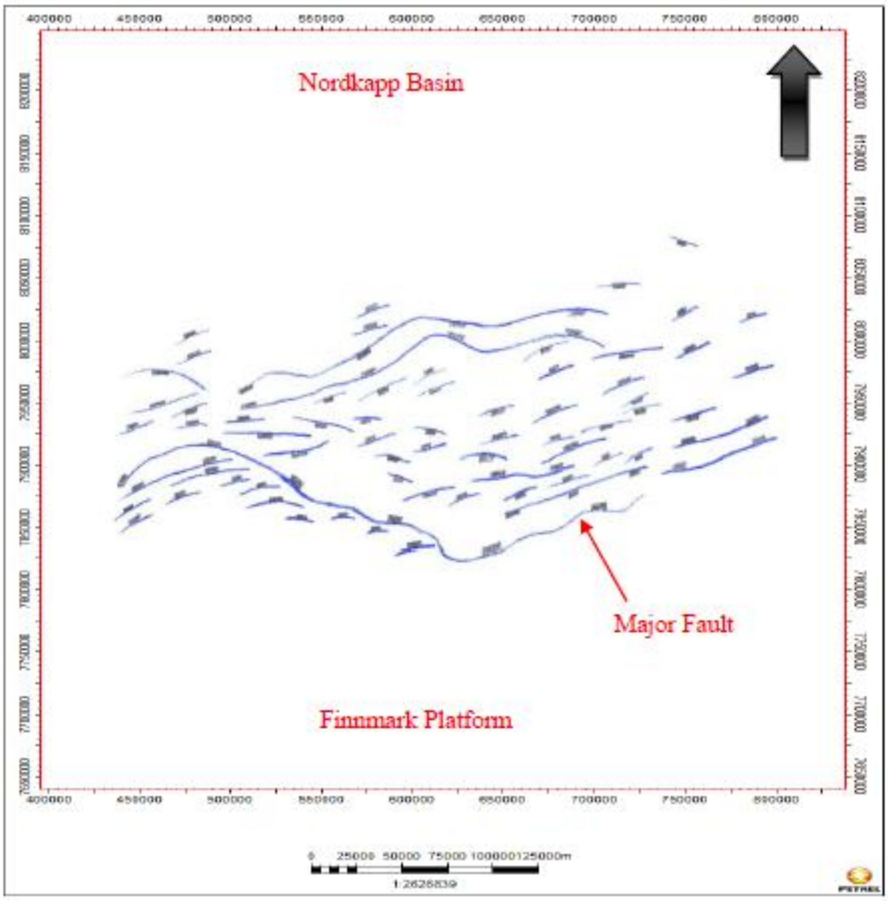


Figure 4.19: Structural trend map, BC.

4.5 Fault activity

There are several faults that are interpreted on the seismic data. Along with smaller faults there is one major fault (F1) that can be interpreted on all of the seismic data (2D & 3D) and that fault has penetrated through all of the interpreted horizons. Most of the structures are present between 500 ms and 2000 ms on the seismic data. At the levels deeper that intra Carboniferous 2 there is no pronounced tectonic activity. Nearly all of the faults that are interpreted represent normal faulting. Along with fault activities there are also salt related tectonic events that are observed on some of the 2D seismic lines.

4.5.1 Major fault

The major fault (FI) has affected all of the horizons interpreted at different level. The fault is characterized by high angle and northwards throw that is towards the Nordkapp Basin. Three segments of contrasting strikes are identified, as the strike of the major fault is changing from west to east. In segment 1 the strike is SW-NE, in segment 2 the strike is NW-SE and in segment 3 the strike is SW-NE (Figure 4.1). Fault related drag features are also observed at different levels. On the basis of interpreted seismic data it is very obvious that the intensity of the tectonic activity is very pronounced towards the hanging wall of the major fault as compared to the footwall. Most of the minor faults are parallel to the major fault, and they have the same dip as the major fault (Figures 4.8, 4.9, 4.10).

The major fault represents normal fault geometry indicated by a significant dip of strata on the hanging wall side and the uplifted footwall is indicated by considerable erosion on the seismic data. The deepest seismic reflection that has been penetrated by the major fault is Early Carboniferous. And further continuation of the fault downwards may suggest that the fault is probably approaching the basement.

To observe the fault throw and sediments thickness variation across the major fault from west to east, measurements have been taken on selected 2D lines at different interpreted levels. The measurements are in time (ms) (Figures 4.1). Due to the limitations in the data these measurements are taken in time instead of depth.

In case of fault throw, results show that on the eastern side there are low values for the fault throw at different interpreted levels. While on the western side at same levels values are high. This indicated that that the throw of the fault is increasing from east to west. Which shows the tectonic activity is more pronounced along the major fault on the western side as compared to the eastern side. (Tables 4.6, 4.7, 4.8, Figures 4.8, 4.9, 4.10).

For thickness variation, results show that on the hanging wall of the major fault the thickness of the strata at different levels is greater as compared to the footwall. The overall thickness trend is increasing towards north. This indicates that at the time of deposition of sediments there was greater accommodation space available for sediments and also the major fault was active during the deposition resulting in fault controlled deposition of sediments (Figures 4.20, 4.21, 4.22) (Tables 4.2,4.3,4.4,4.5).

Table 4.2: Measurements for time-thickness variation between C1and LP.

Line	**Footwall LP**	**Footwall C1**	**Hanging wall LP**	**Hanging wall C1**	**Difference**
E	1800 ms	2440 ms	2050 ms	2600 ms	410 ms (approx)
B	1470 ms	1600 ms	1820 ms	2030 ms	780 ms (approx)
A	1700 ms	2950 ms	2880 ms	3420 ms	1650 ms (approx)

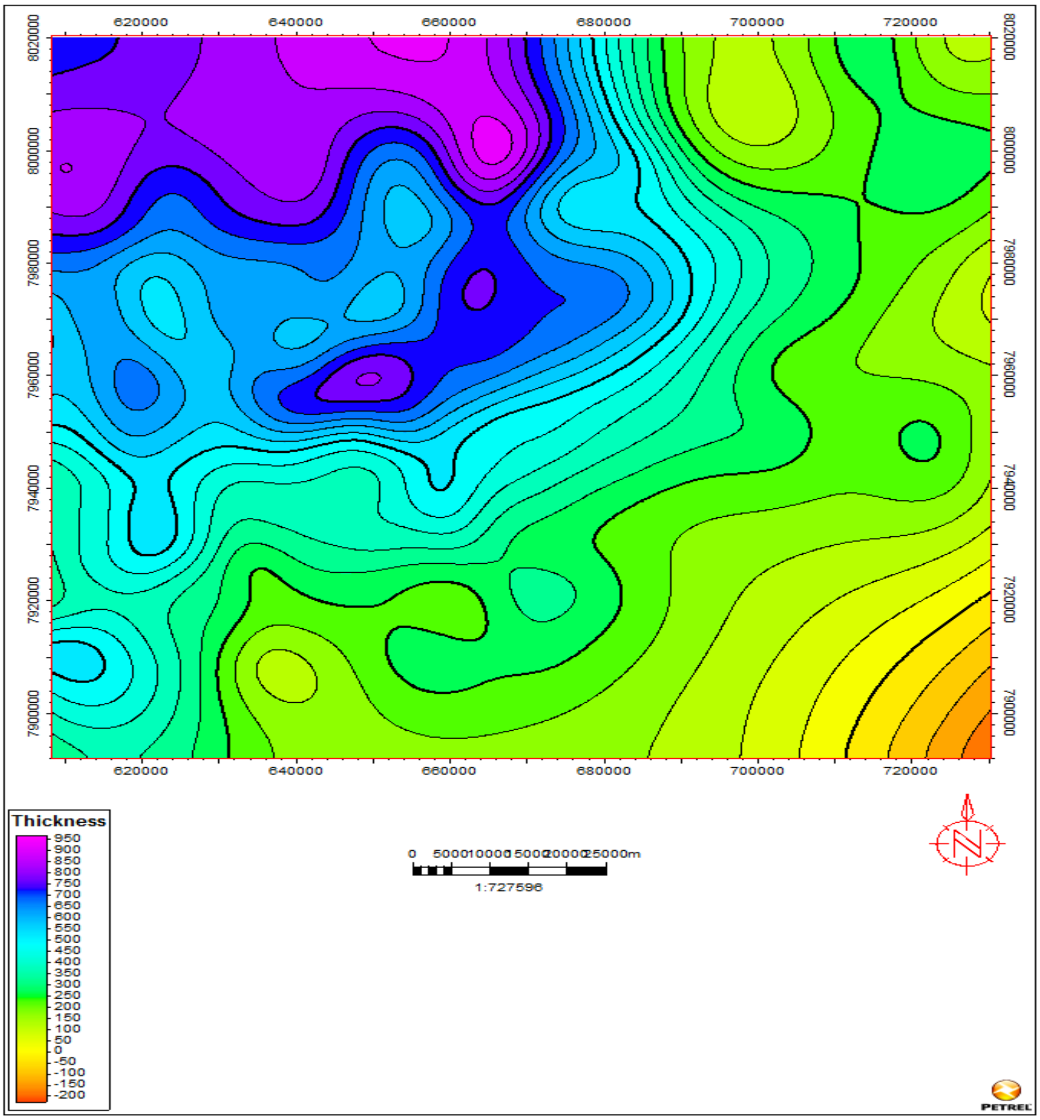


Figure 4.20: Time-thickness map between C1 and LP.

Table 4.3: Measurements for time-thickness variation between LP and ET.

Line	**Footwall ET**	**Footwall LP**	**Hanging wall ET**	**Hanging wall LP**	**Difference**
E	1360 ms	1800 ms	1460 ms	2050 ms	350 ms (approx)
B	1190 ms	1470 ms	1330 ms	1820 ms	490 ms (approx)
A	1700 ms	2525 ms	2200 ms	2880 ms	855 ms (approx)

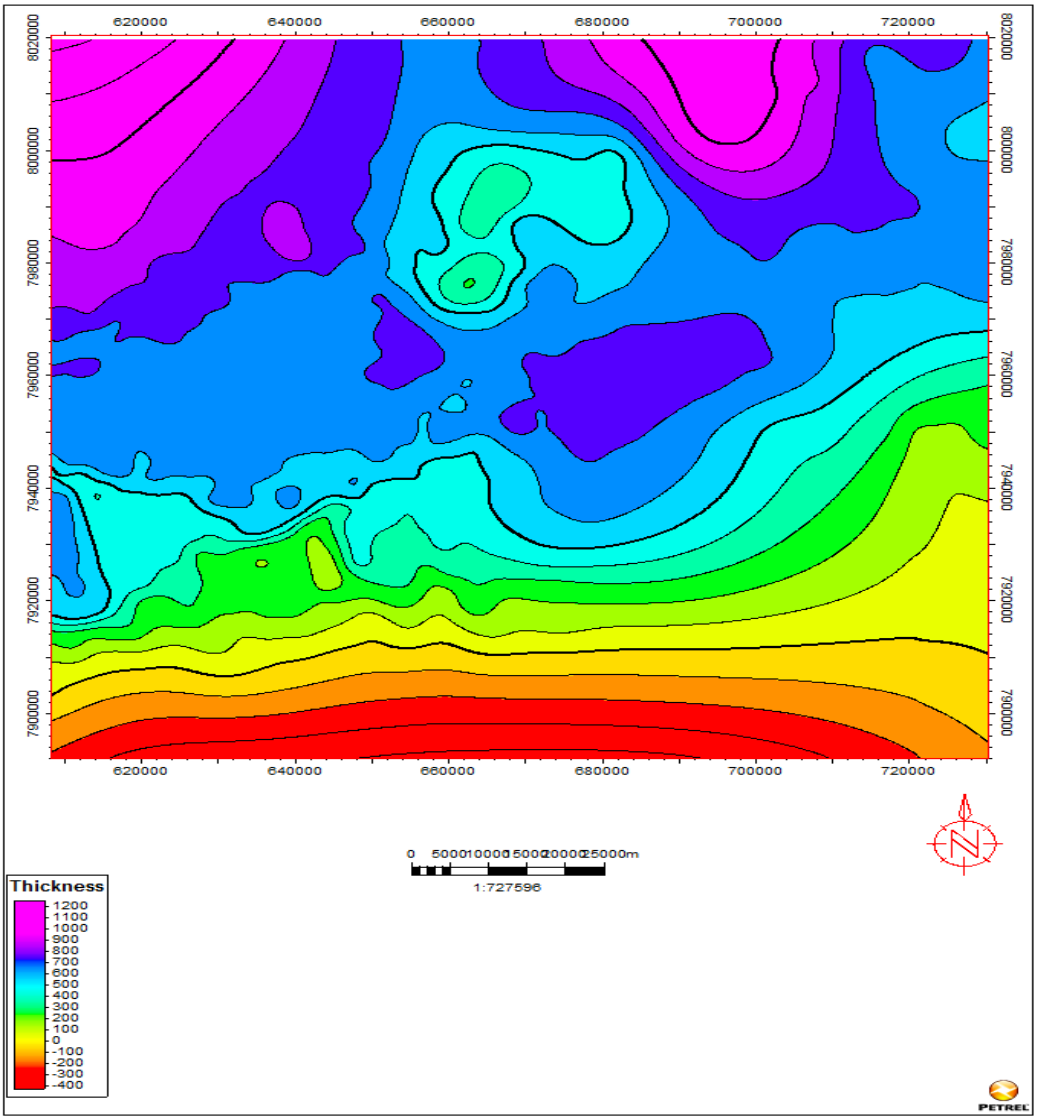


Figure 4.21: Time-thickness map between LP and ET.

Table 4.4: Measurements for time-thickness variation between ET and BC

Line	Footwall BC	Footwall ET	Hanging wall BC	Hanging wall ET	Difference
E	900 ms	1360 ms	950 ms	1460 ms	150 ms (approx)
B	750 ms	1190 ms	800 ms	1330 ms	190 ms (approx)
A	1180 ms	1700 ms	1365 ms	2200 ms	685 ms (approx)

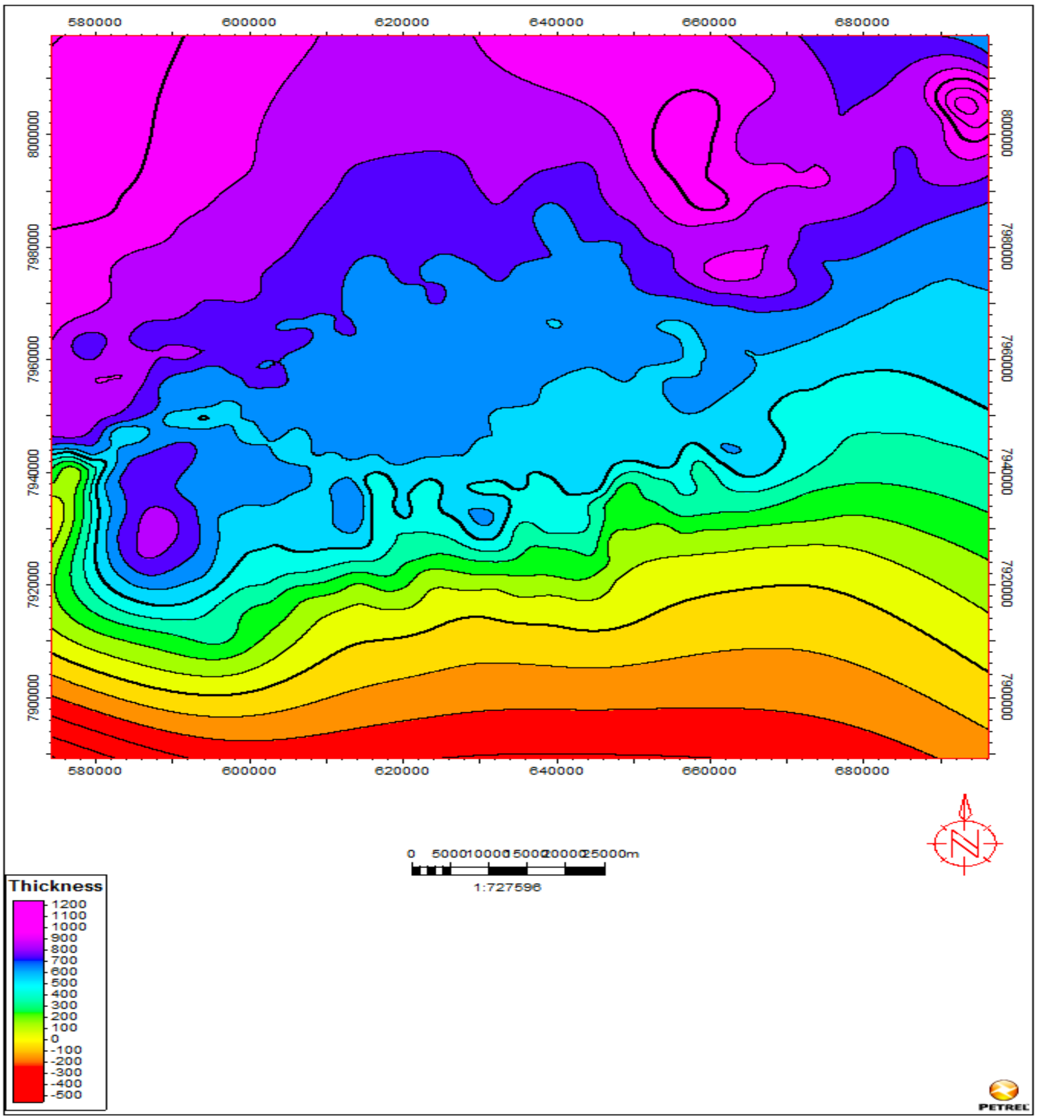


Figure 4.22: Time-thickness map between ET and BC.

Table 4.5: Measurement for fault throws for C1.

Line	Footwall	Hangingwall	Difference
E	2440 ms	2600 ms	160 ms (approx)
B	1600 ms	2030 ms	430 ms (approx)
A	2950 ms	3420 ms	470 ms (approx)

Table 4.6: Measurement for fault throws for LP.

Line	Footwall	Hangingwall	Difference
E	1800 ms	2050 ms	250 ms (approx)
B	1470 ms	1820 ms	350 ms (approx)
A	2525 ms	2880 ms	355 ms (approx)

Table 4.7: Measurement for fault throws for ET.

Line	Footwall	Hanging wall	Difference
E	1360 ms	1460 ms	100 ms (approx)
B	1190 ms	1330 ms	140 ms (approx)
A	1700 ms	2200 ms	500 ms (approx)

Table 4.8: Measurement for fault throws for BC.

Line	**Footwall**	**Hanging wall**	**Difference**
E	900 ms	950 ms	50 ms (approx)
B	750 ms	800 ms	50 ms (approx)
A	1180 ms	1365 ms	185 ms (approx)

4.5.2 Structural style

To study the fault activity across the study area, it has been divided into three different segments on the basis of the orientation of major fault (F1) (Figure 4.1).

4.5.2.1 Segment 1

This segment represents the western part of the study are (Figure 4.1). Along the major fault there is a significant displacement at different interpreted levels. At CI, LP, ET and BC levels, sediments thickness across the fault is varying a lot. Towards the footwall the thickness of sediments is less as compared to the hanging wall. This can be the result of fault activation during sedimentation. The major fault has penetrated through the deepest seismic reflection that belongs to the Early Carboniferous times. This may indicate that the fault may have originated from the basement. In this segment there is a pronounced subsidence occurred indicated by the sediments thickness and the dip of the strata along the major fault (Section 4.5.1, Figure 4.8, 4.9, 4.10).

Minor fault activity is restricted down to Early Triassic level. Below this level due to poor data quality structures are hard to recognize. Most of the faults are dominant at Base Cretaceous level. Normal faults are abundant along with associated structures such as horst and graben. The dominant strike of the minor faults is NE-SW. On the hanging close to the major fault at Base Cretaceous level there are rotated fault blocks associated with rift events. Synthetic faults are dominant along with antithetic faults that are rare indicated by the dip direction with respect to the major fault (Figures 4.13, 4.15, 4.17, 4.19).

Segment 1 can be divided into two parts.

- S1-A: Characterize the footwall of the major fault (F1). Most faults are present between Base Cretaceous and Triassic levels. Synthetic normal faults are dominant along with few graben structures. Cretaceous, Triassic and Permian sediments are eroded. Abundant NE-SW striking faults along with few NW-SE strikes.

- S1-B: Marks the hanging wall of the major fault (F1). There is a northwards flexuring of strata, presence of sedimentary wedges along with thick sedimentary sequences in between different interpreted levels. Rotation of fault blocks associated with rifting and few signs of inversion at Base Cretaceous level. Most of the fault activity is between Base Cretaceous and Late Permian. Several graben structures along with horst structures. Few antithetic faults along with synthetic faults which are abundant. NE-SW strike of the minor is dominant. Few signs of inversion indicated by small scale reverse faults at Base Cretaceous level.

4.5.2.2 Segment 2

The segment is located in the centre of the study area (Figure 4.1). The displacement along the major fault at different level is apparent. The thickness of sediment towards the hanging wall is greater as compared t the footwall. However this thickness variation across the fault is less as compared to the segment 1. Here again Early Carboniferous seismic horizon has been penetrated by the major fault. As compared to the segment 1 the subsidence along the major fault is less (Section 4.5.1, Figure 4.8, 4.9, 4.10).

The intensity of faulting is greater in this segment as compared to the segment 1 apparent by the faults population on the hanging wall and the foot wall. Fault activity is dominant on the hanging wall, whereas on the foot wall there are few faults. Normal faults are plentiful along with Graben structures. Except C2 almost all of the interpreted levels show considerable tectonic activity. Two contrasting striking trends of smaller faults are present, NW-SE and NE-SW. Most of the faults are synthetic indicated by their dip with respect to the major fault (Figures 4.13, 4.15, 4.17, 4.19).

Segment 2 can be divided into two parts.

- S2-A: Characterize the footwall of the major fault (F1). Except Early Cretaceous rest of the horizons show significant tectonic activity. Synthetic normal faults are dominant along with few graben structures. Cretaceous, Triassic and Permian sediments are eroded. Abundant NE-SW striking faults along with few NW-SE strikes.

- S2-B: Marks the hanging wall of the major fault (F1). There is a northwards flexuring of strata, presence of sedimentary wedges along with thick sedimentary sequences in between different interpreted levels. Rotation of fault blocks associated with rifting along with minor indication of inversion at Base Cretaceous level. Like footwall Except Early Cretaceous rest of the horizons show significant tectonic activity. Plentiful graben structures along with horst structures. Few antithetic faults along with synthetic faults which are abundant. NE-SW strike of the minor is dominant. Few signs of inversion at Base Cretaceous level marked by small scale reverse faults. S2-B seems to be more tectonically disturb as compared to the S1-B.

4.5.2.3 Segment 3

This segment marks the eastern part of the study area (Figure 4.1). As compared to the segments 1 and 2 the displacement along the major fault in this segment is less. However again the sediments thickness is greater towards the hanging wall relative to the footwall. This can be the result of fault activation during sedimentation. The amount of subsidence relative to the segment 1 and 2 is less (Section 4.5.1, Figure 4.8, 4.9, 4.10).

The deformation style is almost similar to the segment 2. Hanging wall seems to be very deformed. The dominant strike of the smaller fault is NE-SW. There are two main features that are recognized in this segment. A dome shaped structures at Early Carboniferous level towards the hanging wall of the major fault and Halokinesis. On the basis of structural trend the segment can be divided into two parts (Figures 4.13, 4.15, 4.17, 4.19).

- S3-A: Describes the footwall of the major fault (F1). Scattered fault pattern from Base Cretaceous to Late Permian. Very few graben structures. Plentiful synthetic faults. Trassic and Base Cretaceous horizons seems to be more affected by erosion then rest of the levels.

- S3-B: Characterize the hanging wall of the major fault (F1). Tectonic deformation of S3-B seems to be similar to the S2-B. There are few signs of compressional events along with Halokinesis.

4.5.3 Structures at interpreted horizons

Horizon interpreted at Early Carboniferous level is different from the others. Since it has been interpreted at greater depth its extent is limited between major fault F1 and F2. On smaller scale there are no prominent structural activities observed at this level. However on few seismic lines there is a dome like structure that is observed on the hanging wall side of the major fault which is very clear particularly on 3D data (Figure 4.23).

At Late Carboniferous level there is no prominent tectonic activity on smaller scale. On the footwall side of major fault (F1) there are few normal faults present at this level. Also the strata is cut by major fault F1 and F2 resulting in the formation of graben structure on larger scale. The throw along the major fault at this level is high (Figures 4.13, 4.25).

LP is tectonically less disturbed. It is also dominated by normal faults and graben structures on smaller scale. Most of the faults and other structures at this level are dominant on the hanging wall side of the major fault that is towards the Nordkapp Basin. On the footwall side of the major fault it has been cut by many normal faults but still it’s very much continuous on the seismic data. Throw of the major fault at this level is greater. It has been also affected by salt movements (Figures 4.15, 4.25).

ET has almost the same structural trend as LP. Normal faults are abundant along with graben structures. Tectonic activity is dominant on the hanging wall of the major fault at this level. On the footwall there are few normal faults however there is no prominent tectonic activity at this level. Throw along the fault at this level is high. The effect of salt related movements can also be observed at this level (Figures 4.17, 4.25).

BC is a structurally disturbed horizon but still can be easily interpreted on the seismic data. It is dominated by normal faults and graben structures along with horst structures which are rare. Presence of few reverse faults is observed. Rotation of fault blocks can be observed near to the major fault at this level along with sediments wedge on few seismic lines. Most of the faults and other structures at this level are dominant on the hanging wall side of the major fault that is towards the Nordkapp Basin. On the footwall side of the major fault the horizon is mostly missing on the seismic data because of the erosion which resulted due to the uplift. Throw of the major fault at this level is moderate. On some of the seismic data salt related tectonic activity has also been observed at this level (Figure 4.19, 4.25).

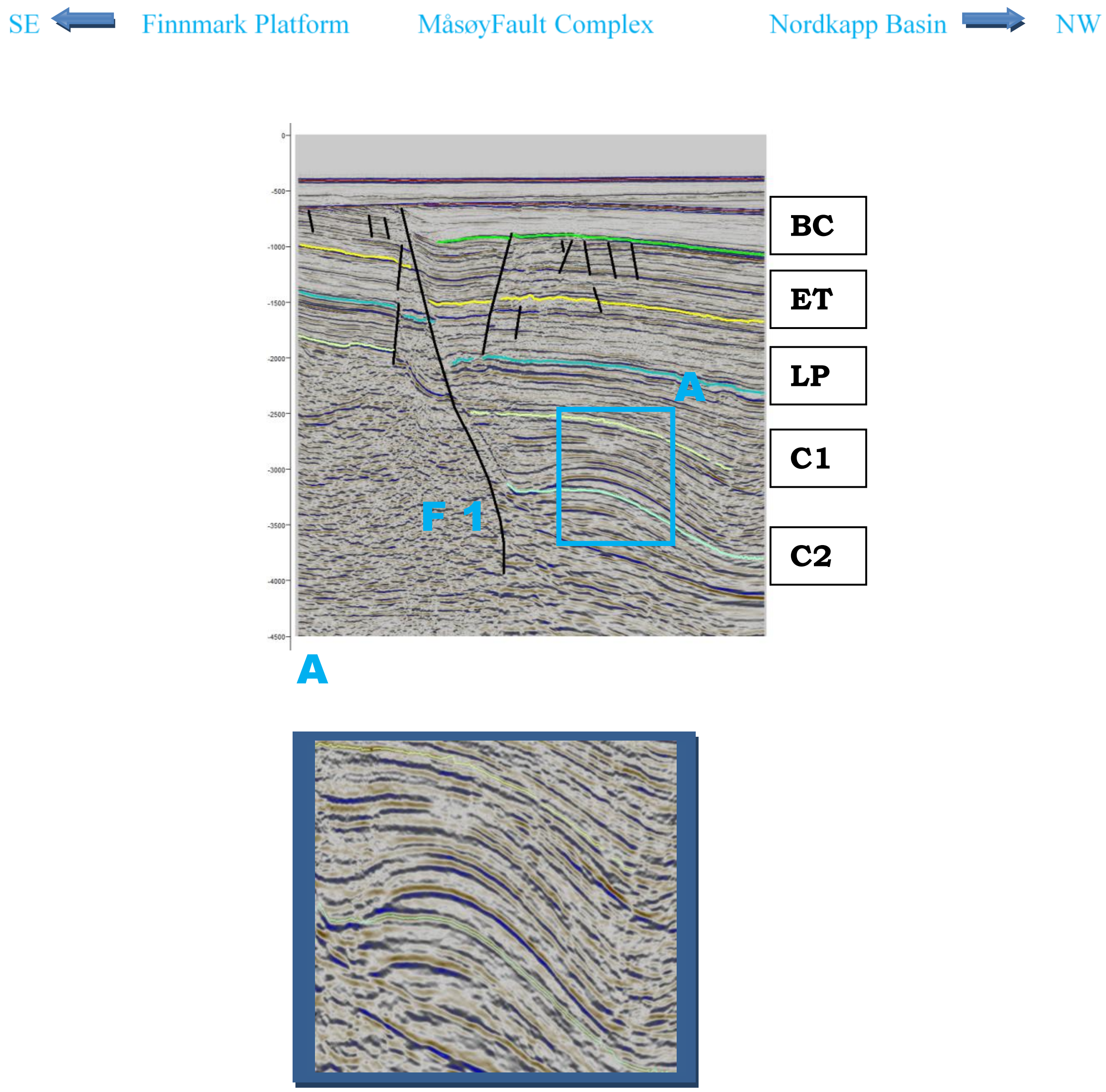


Figure 4.23: 3D random line (A: Dome structure between C1 and C2) (see Table 4.1 for age and interpreted horizons).

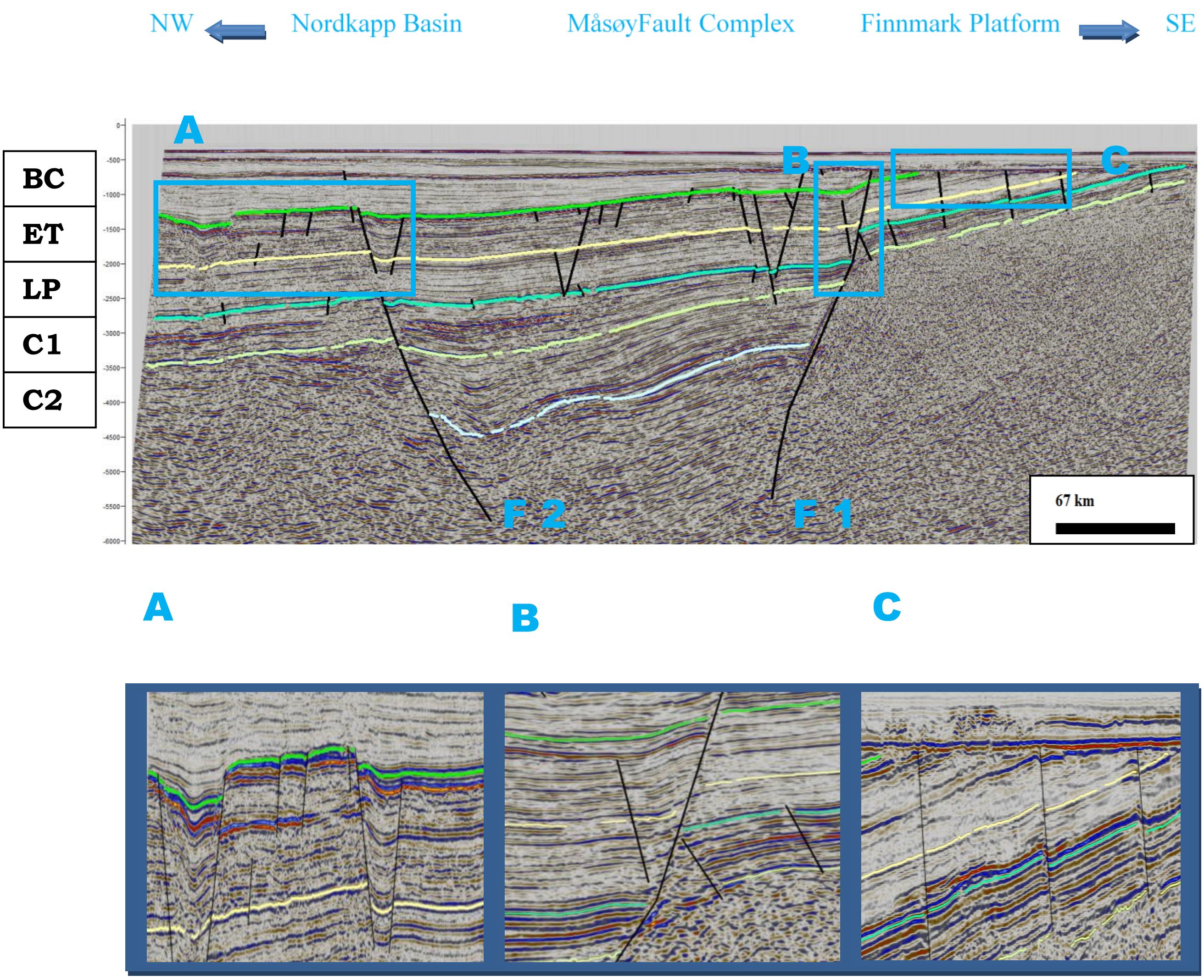


Figure 4.24: 2D seismic line C showing Structures and faults interpreted at different levels (A: graben and horst structures, B: throw of horizons with respect to fault, C: erosional truncation) (see Figure 4.1 for location and Table 4.1 for age of interpreted horizons).

4.6 Halokinesis

On the NE side of the 2D seismic survey there are salt related tectonic events that are observed on few lines. Salt has a mobile nature, it means that when it's under pressure it flows, cutting through the sediments. Similar behavior of salt can be seen here. It has penetrated through the strata making it difficult to interpret. Also due to the same event it is almost impossible to interpret the horizons at Carboniferous level, as salt result in chaotic reflections (Figure 4.25).

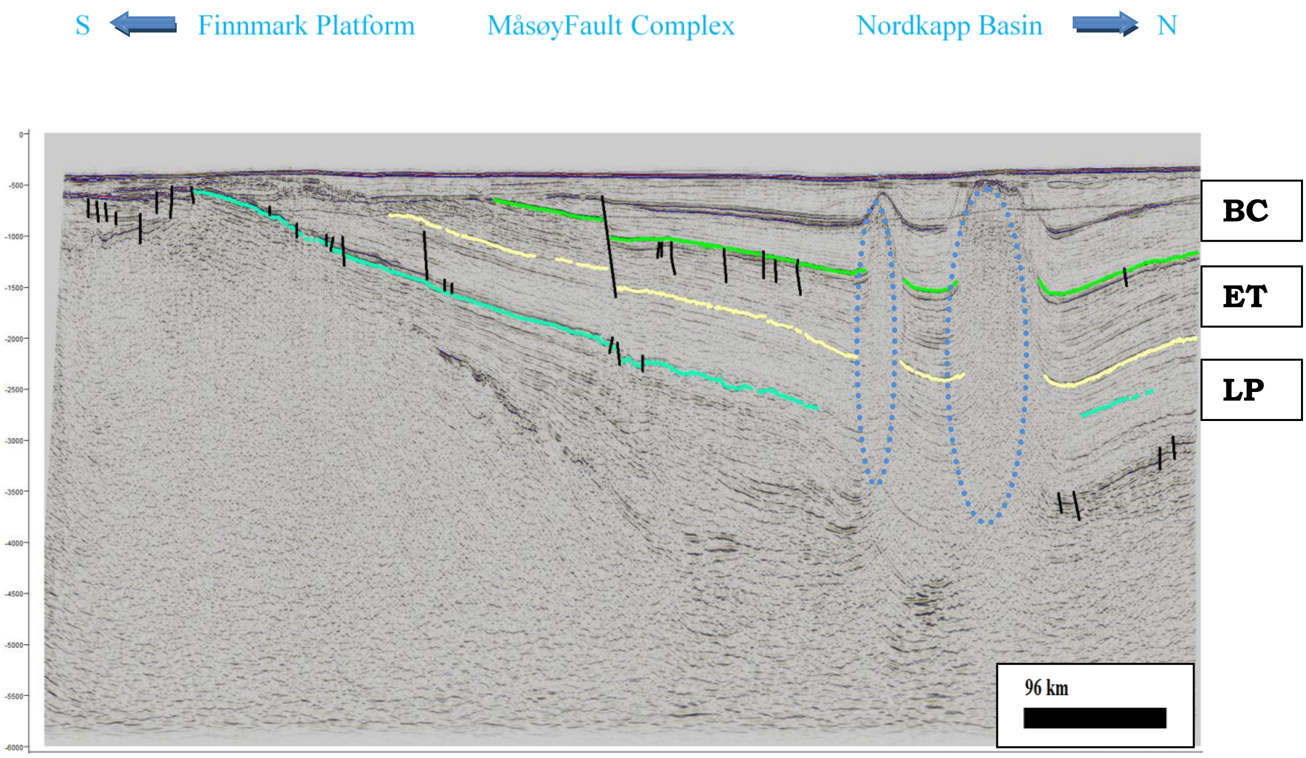


Figure 4.25: Seismic line F showing salt diapir indicated by blue circle (see Figure 4.1 for location and Table 4.1 for age of interpreted horizons).

5 Discussion

This chapter involves the study of tectonic evolution of the Måsøy Fault Complex, associated with regional tectonic events using present results and previous studies. Main focus will be upon following parameters.

1. Master fault reactivation.
2. Subsidence.
3. Impact of halokinesis.
4. Fault genesis.

5.1 Evolution of the Måsøy Fault Complex

5.1.1 Devonian to Early Carboniferous

Gabrielsen et al. (1990) suggested that the Måsøy Fault Complex is associated with basement involved tectonic activity. Their proposition can be illustrated by the fact that the deepest seismic reflection interpreted on the seismic data is Early Carboniferous and further continuation of the master fault below this level is observed. The formation of Nordkapp Basin is associated with Late Devonian to Early Carboniferous tectonic events (Koyi et al. 1993) and the Måsøy Fault Complex is one of the basin marginal faults of the Nordkapp Basin. These remarks clarify the origin of the Måsøy Fault Complex. Faleide et al. (1984) proposed that the rifting initiated in Late Devonian to Early Carboniferous. Similar comments are illustrated by Glørstad-Clark et al. (2010). The onset of rifting is marked by the deep penetration of the master fault below Early Carboniferous level. There is not any significant vertical displacement along the master fault at this level. The sediments are very uniform and the hanging wall strata are bending away from the fault plane (Figure 4.9, 5.4).

5.1.2 Mid Carboniferous to Mid Permian

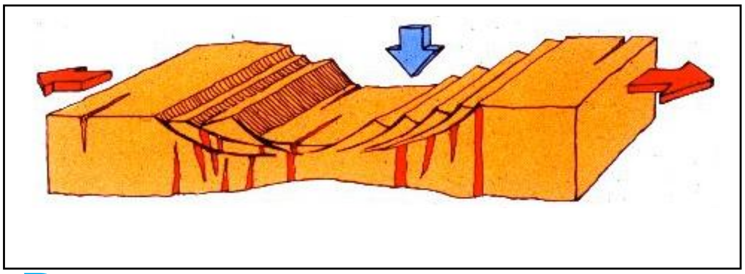
Glørstad-Clark et al. (2010) suggested Late Carboniferous to Late Permian as second phase of rifting. Active streaching stage is indicated by significant displacement along the master fault.

Several normal and reverse drag features are observed at different levels. In normal drag strata is convex towards the slip direction, typically results due to the resistance to slip (Hamblin 1965, Biddle and Christie-Blick 1985). In case of reverse drag the strata is concave towards the slip direction (Hamblin 1965). Similar behavior has been observed in the study area. Presence of drag features is another indication of the activation of master fault also they may indicate the existence of various types of folds associated normal faulting (Figure 4.10). Since the master fault was active during different times there is a possibility that these drag features were formed due to friction induced drag.

In the study area between Early to Late Carboniferous there are dome like structures marked by reverse drag (Figure 4.23). Since Måsøy Fault Complex is associated with Nordkapp Basin there is a possibility that these structures may represent halokinesis. Tectonic activity is partially influenced by halokinesis (Gabrielsen et al. 1990). Above stated dome structure is observed towards the hangingwall of the major fault. Further association of the halokinesis with the Måsøy Fault Complex can be justified by following comment of Koyi et al. (1993), they suggested that during Late Carboniferous a salt layer precipitated in the basin and traces of that salt are present towards the basin margins. Considering the 2D seismic survey in the study area the orientation of these salt related dome structures is towards the NE termination of the master fault. Koyi et al. (1993) proposed that salt structures are oriented NE-SW and are present parallel to the basin margin faults that are associated with thick skin tectonics. Salt has a mobile nature, it means that when it is under pressure it flows, resulting in compression or faulting of the strata. Same nature of salt has been observed in the study area. Koyi et al. (1993) commented that reactivation of deep rooted faults associated with the Nordkapp Basin confined and deformed the salt structures near or above the basement involved faults.

Due to continuous subsidence accommodation structures may develop (Gabrielsen 1986). Growth fault geometry is pointed out by sediments thickness variations across the master fault and increase in displacement down dip of the master fault. Dennis (1967) suggested that this situation characterize the activation of fault during deposition of sediments. These features may indicate syn-sedimentary successions (Section 4.5, Figure 5.1, 5.4).

A



B

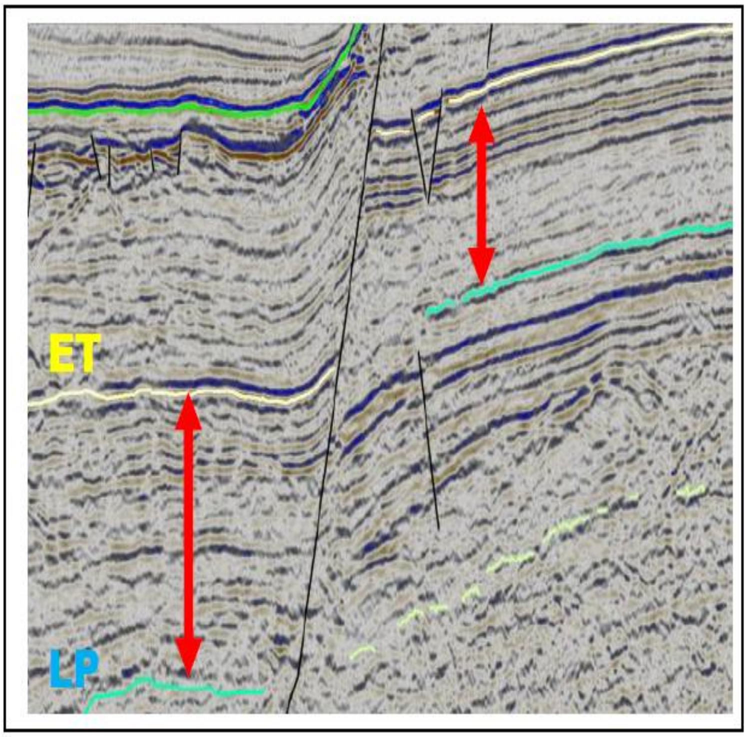


Figure 5.1: A: Stress system during active stretching along with subsidence (Gabrielsen 1986), B: Growth faulting indicated by thickness variation across the master fault at LP and ET levels. LP is showing reverse drag towards the hanging wall and ET is showing normal drag.

5.1.3 Late Permian to Mid Jurassic

Late Permian to Triassic transition marks the onset of regional subsidence along with the development of sag basins in the Barents Sea (Glørstad-Clark et al. 2010). As stated above, growth fault geometry is pointed out by sediments thickness variations across the master fault and increase in displacement down dip of the master fault. At this level hanging wall of the master fault is characterized by thick sedimentary sequence as compared to the footwall. Consequence of fault controlled subsidence. As proposed by Glørstad-Clark et al. (2010) that subsidence was also accompanied by rift related faulting in some areas. Further this state can be explained by the fact that the tectonic activity is unlikely to occur simultaneously throughout the entire basin. This can be due to the thermal in homogeneities, variations in structural configurations etc (Gabrielsen 1986). The interplay of both of the elements including active faulting and subsidence resulted in greater accommodation space for the deposition of sediments towards the hanging wall of the master fault. This is indicated by thick sedimentary sequence towards the hanging wall of the master fault. Further this observation can be justified by Gabrielsen (1986), he proposed that as the fault is active, displacement will be greater and hence the subsidence will also be pronounced resulting in creation of greater accommodation space for sediments towards the hanging wall of the master faults (Figure 5.2).

Presence of salt structure above Late Permian indicates the initiation of halokinesis. According to Gabrielsen et al (1990) Early to middle Triassic times mark the onset of salt movements in the Nordkapp Basin. Influence of halokinesis is restricted towards the hanging of the master fault in the study area. Similar observation has been proposed by Koyi et al. (1993), Diapirs that are rooting to the basement faults indicate dominant sedimentary fills towards the hanging wall of the major faults. The placement of salt diapirs parallel to the basin margin faults indicate that there evolution has been influenced by basement faults. (Figures 4.26, 5.4).

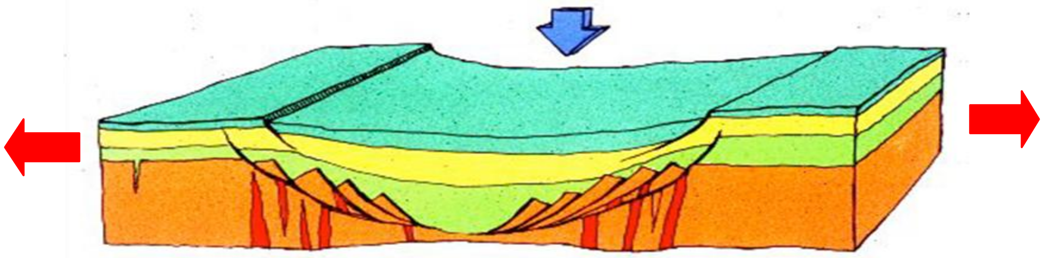


Figure 5.2: Subsidence along with continuous rifting resulting in greater accommodation space in the study area (modified from Gabrielsen 1986).

5.1.4 Late Jurassic to Early Cretaceous

In the study area rotated fault blocks at Base Cretaceous level indicate the syn-rift phase. As proposed by Gabrielsen et al. (1990) in Mid Jurassic block faulting started and got intense during Late Jurassic and Early Cretaceous. Again the growth fault geometry is observed at this level suggesting the fault controlled subsidence in the younger sediments. Presence of master fault in shallow sediments can be clarify by Halstead (1975), Eynon (1981), Johnson and Dingwall (1981) as they suggested that the effect of deep rooted faults in the shallow sediments is identified at different places in the North Sea, the influence of the same process can also be present in the Barents Sea (Gabrielsen and Ramberg 1979, Gabrielsen 1984). Presence of minor reverse faults at Base Cretaceous level may indicate the influence of inversion. As suggested by Glørstad-Clark et al. (2010) that during Mid Jurassic to Mid Cretaceous extension was accompanied by strike slip movements which resulted in inversion (Figure 5.3).

Early Triassic and Base Cretaceous horizons are pushed by salt. This resulted in the truncation of sediments at these levels against the salt diapirs. Same development has been identified by Gabrielsen et al. (1990), Salt that was deposited during Early to middle Triassic times pushed the Triassic and Cretaceous sediments, which resulted in truncation of these sediments against the diapirs. Due to Halokinesis there is a significant tilting and bending of sediments at Early Triassic and Base Cretaceous level. Koyi et al. (1993) made the same suggestions regarding Halokinesis at these levels. At the NE termination of the master fault the continuity of the master fault below Early Triassic level is not clear. There is a possibility that the penetration of master fault into deeper sediments has been obscured by the

Halokinesis. Koyi et al. (1993) proposed the same comment that the influence of basement involved marginal faults of the Nordkapp Basin is affected by the existence of Halokinesis. (Figures 5.3, 4.26, 5.4).

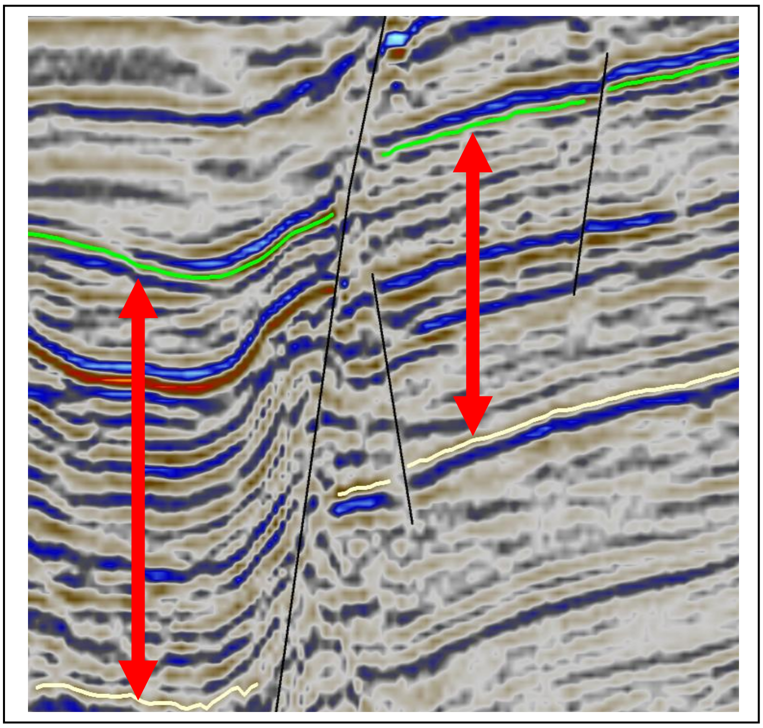


Figure 5.3: Growth faulting at ET and BC levels, sediments thicknesses across the fault are indicated by the arrow. Normal drag at both levels.

5.1.5 Late Cretaceous to Recent

Cretaceous to Paleocene transition is marked by platform uplift (Glørstad et al. 2010). This resulted into footwall uplift of the master fault in the study area. Thick post rift strata got eroded along with partial erosion of Late Permian, Early Triassic and Base Cretaceous sediments, resulting in an unconformable contact of these sediments with the Tertiary strata. The unconformity that created due to erosional uplift is very well defined on the seismic data (Figures 4.25, 5.4).

Rapid sedimentation of Cretaceous and Tertiary times, influence the shape of salt diapirs as they coned upward into the sediments. Similar behavior has been reported by (Koyi et al. 1993) (Figure 4.26, 5.4).

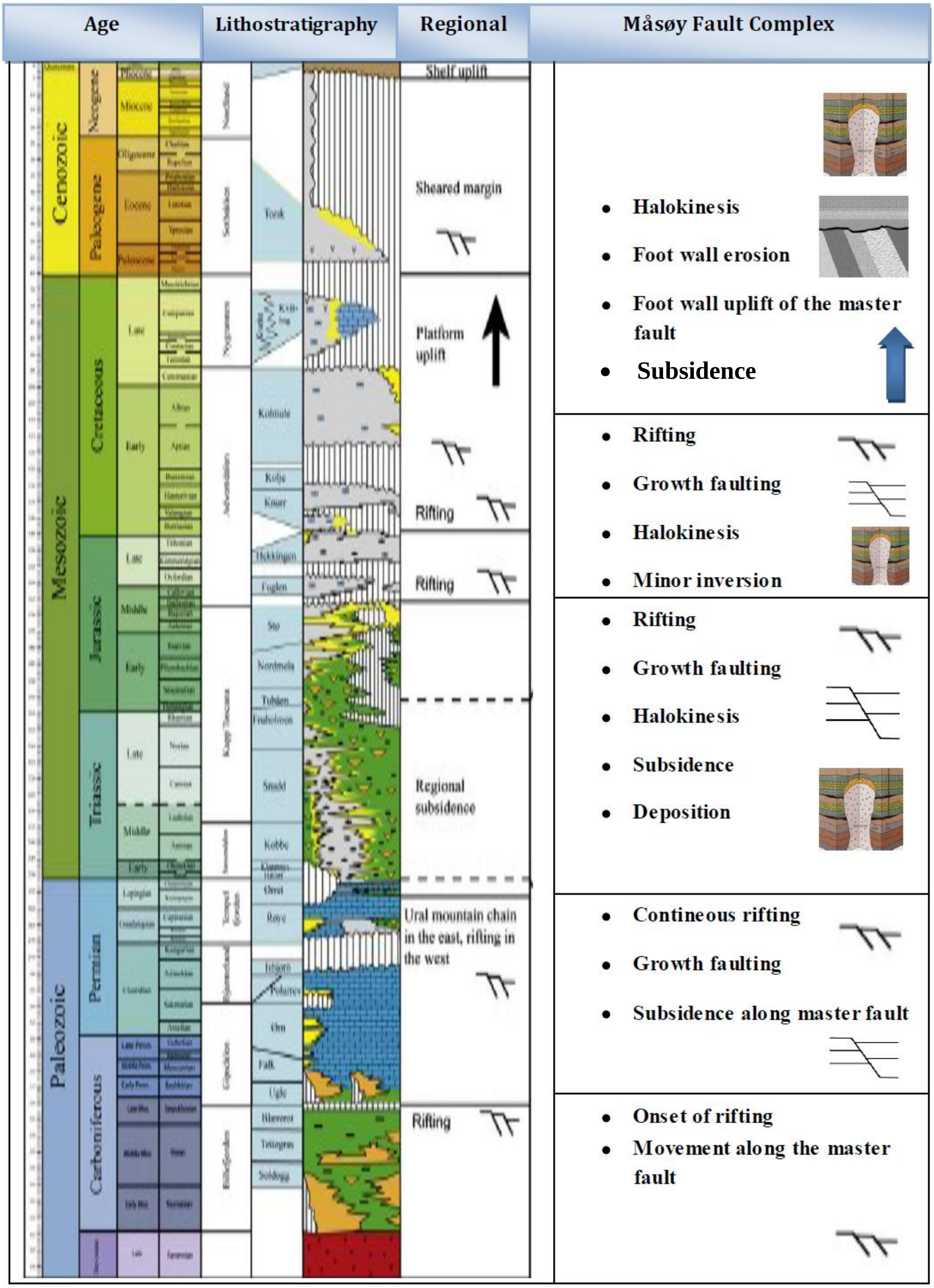


Figure 5.4: Evolution of Måsøy Fault Complex (modified from Glørstad-Clark et al. 2010).

5.2 Fault genesis

Following study has been carried out in order to figure out the local impact of regional tectonics. Only hanging wall and the foot wall of the master fault are considered in this case.

5.2.1 Early to Late Carboniferous

In the study area at this level strata are bounded by two faults, including major fault (F1) and F2. The presence of these faults at this level may suggest the initial tectonic activity that took place in the area. Gudlaugsson et al. (1998) proposed that Late Devonian to Early Carboniferous extension associated with the initial rifting between Greenland and Norway is the oldest event that can be observed in the western Barents Sea. Due to limitation in data quality minor tectonic structures are difficult to interpret (Figure 4.8).

5.2.2 Late Carboniferous to Late Permian

This level marks the onset of minor fault activity in the study area. Faults of two contrasting strikes are observed including NW-SE and NE-SW. Gabrielsen et al. (1990) suggested that during Late Carboniferous to Early Permian main structural elements in the western part were oriented NE-SW and NNE-SSW. Concentration of fault activity is more towards the hanging wall as compared to the footwall. Most of the faults present at this level indicate synthetic behavior and positioned parallel to sub parallel with respect to each other. Active stretching stage results in complex hanging wall geometry (Gabrielsen 1986) (Figures 4.8, 4.13, 4.15).

5.2.3 Late Permian to Early Triassic

Late Permian was associated with regional subsidence (Glørstad-Clark et al. 2010). This period is marked by increase in faulting along with the development of horst and graben structures which are abundant. Due to constant subsidence next to the major fault graben may develop parallel to the major fault (Gabrielsen 1986). Planer normal faults are dominant at this level. The dominant fault orientation is marked by NE-SW strike (Figures 4.8, 4.15, 4.17).

5.2.4 Early Triassic to Early Cretaceous

Structurally complex level in the study area characterized by plentiful faulting activity along with horst and graben structures. Gabrielsen et al. (1990) proposed that in Mid Jurassic block faulting started and got intense during Late Jurassic and Early Cretaceous. Similar features are been observed in the study area. During early cretaceous there was a local influence of inversion (Gabrielsen et al. 1990). Presence of reverse faults at this level may provide the evidence of inversion. The existence of reverse faulting in an extensional regime indicates reverse reactivation of normal faults (Gabrielsen 1986). Williams et al. (1989) recommended that positive inversion is the result of contraction in an extensional regime. In the study area at this level influence of tectonic activity is very pronounced towards the hangingwall as compared to the footwall, which is apparent in the data. The hanging wall of the major fault in the area is reported to be severely damaged and may indicate inversion (Gabrielsen & Faerseth 1989). Again NE-SW oriented faults are dominant. Gabrielsen et al. (1990) suggested the same comments (Figures 4.8, 4.17, 4.19).

6. Conclusion

Results show that the Måsøy Fault Complex is an extentional structure. The study area underwent two different rift phases. The first rift phase initiated during Late Devonian to Early Carboniferous and the second rifting event took place during Mid Jurassic to Early Cretaceous. On the basis of interpreted seismic data it is observed that the major fault in the area is associated with thick skin tectonism. Gabrielsen et al. (1990) propose the same remarks. On the basis of measurements that are taken across the fault (section 5.4) I would suggest that the major fault in the area was active during different rift phases. Even at the time of regional subsidence the fault complex show pronounced tectonic activity. Similar observations were made by Glørstad-Clark et al. (2010).

As stated above that study area is influenced by two rift phases. The subsidence after each rift phase was accompanied by rifting. First post rift stage show more pronounced effect of subsidence and faulting as compared to the second rift phase indicated by the considerable displacements towards the hanging wall below Jurassic level (Section 5.4). Towards the hanging wall the trend of sediments displacement is increasing along the strike of the master fault from east to west.

Partial impact of halokinesis has been observed in the study area. Salt activity is restricted towards the NE part of the 2D seismic survey. Towards the NE termination of the major fault the continuity of the fault below the Triassic level seems to be obscured by the presence of halokinesis. Also due to chaotic reflections Carboniferous reflections are difficult to interpret.

Considering the hanging wall and the foot wall of the master fault, hanging wall is more deformed. Similar observation has been done by Gabrielsen and Færseth (1989). Impact of inversion seems to be less and the dominant strike of the minor faults is NE-SW. Gabrielsen et al (1990) proposed the same comments.

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